Historic England

Scientific Dating

Leicester's Building, Kenilworth Castle Castle Green, Kenilworth, Warwickshire Tree-Ring Analysis of Timbers

Alison Arnold, Robert Howard and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 46-2015

Leicester's Building, Kenilworth Castle
Castle Green, Kenilworth
Warwickshire

Tree-Ring Analysis of Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

NGR: SP 27312 72120

ISSN 2059-4453 (Online)

The Research Report Series incorporates reports by Historic England's expert teams and other researchers. 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.

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

Opinions expressed in Research Reports are those of the author(s) and are not necessarily those of Historic England.

SUMMARY
Dendrochronological analysis was undertaken on 43 of 52 samples obtained from door and window lintels within Leicester's Building at Kenilworth Castle, and from timber to the landings of a corner turret here (nine of the 52 samples having too few rings for reliable dating purposes). This analysis produced two dated site chronologies, the first comprising nine samples and being 128 rings long, the second comprising 17 samples and being 192 rings long. These ring sequences were respectively dated as spanning the years AD 1423–1550 and AD 1362–1553. Three further samples were dated individually. Of the measured samples, 14 remain ungrouped and undated. Interpretation of the sapwood on the dated samples indicates that while one timber was probably felled in the late-fifteenth century, the vast majority of dated timbers are likely to belong to the construction works undertaken by Robert Dudley, documented as occurring in AD 1570–72 with subsequent alterations undertaken before AD 1575. This analysis thus demonstrates the widespread presence of timbers associated with the primary construction of this building and/or alterations made very shortly afterwards.

CONTRIBUTORS
Alison Arnold, Robert Howard and Cathy Tyers

ACKNOWLEDGEMENTS
We would particularly like to thank Joyce Christie, the project architect of Purcell UK Ltd, for her constant help and attention in arranging access for sampling. We would also like to thank the on-site English Heritage staff who were enthusiastic and supportive throughout the many site visits and unfailingly helped with access for sampling. Finally, we would like to thank Shahina Farid, Historic England Scientific Dating Team, for commissioning this programme of tree-ring dating, and for providing information and advice throughout this analysis.

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

HISTORIC ENVIRONMENT RECORD OFFICE
Warwickshire Historic Environment Record
Museum Field Services
The Butts
Warwickshire CV34 4SS

DATE OF INVESTIGATION
2013–2022

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

Cathy Tyers
Historic England
Cannon Bridge House
23 Dowgate Hill
London EC4R 2YA
cathy.tyers@historicengland.org.uk

CONTENTS

Introduction ... 1
Sampling ... 1
Analysis and Results ... 2
Interpretation ... 3
Individually dated sample KNW-D34 ... 4
Individually dated sample KNW-D50 ... 4
Site chronology KNWDSQ01 ... 4
Site chronology KNWDSQ02 ... 5
Individually dated sample KNW-D52 ... 6
Discussion and Conclusion ... 6
Woodland sources ... 7
Undated samples ... 8
References ... 9
Tables ... 12
Figures ... 18
Data of Measured Samples ... 30
Appendix 1: Tree-Ring Dating ... 40
The Principles of Tree-Ring Dating ... 40
The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory ... 40
1 Inspecting the Building and Sampling the Timbers. ... 40
2. Measuring Ring Widths ... 44
3. Cross-Matching and Dating the Samples ... 45
4. Estimating the Felling Date ... 46
5. Estimating the Date of Construction ... 47
6. Master Chronological Sequences ... 47
7. Ring-Width Indices ... 48
References ... 52
Appendix 2 OxCal code ... 53
KNWDSQ01 and KNWDSQ02 (Fig 8) ... 53
KNWDSQ01 and KNWDSQ02 + KNW-D52 (Fig 9) ... 53
KNW-D34 (Fig 11) ... 54

INTRODUCTION

The extensive and impressive remains of the Grade I listed Kenilworth Castle (List Entry Number 1035327), its associated walls, buildings, and earthworks, stand to the north-west of the town on the main A456 Kenilworth to Coventry road (Fig 1). The first castle on the site, almost certainly of motte-and-bailey type, is believed to have been built by Geoffrey de Clinton in the early twelfth century, the manorial estate of Stoneleigh having been granted to him by Henry I. Later this simple structure was replaced by a fortified keep with a curtain wall. In AD 1173–74 the stronghold was garrisoned for Henry II and became a Royal Castle, which then underwent progressive re-design and fortification over the following centuries.

In AD 1253 Henry III granted the castle to Simon de Montfort, Earl of Leicester, it passing subsequently to his younger son, the Earl of Lancaster, in AD 1265. The Castle then transferred by marriage to John of Gaunt in AD 1361, he being responsible for the Great Hall and for upgrading the site and transforming it into a Royal Palace in the later fourteenth century. From John it went to his son, Henry IV, and then remained in Royal control until AD 1553 when John Dudley obtained Kenilworth Castle from the crown. John Dudley's ownership was short-lived, however, as in the same year he was attained and executed, and the castle returned to Queen Mary. In AD 1563 the castle was restored to Dudley's son, Robert, at that time a favourite of Queen Elizabeth I, who created him Earl of Leicester in AD 1564.

Once installed, Robert Dudley began extensive modernisation at Kenilworth with the construction of a new gatehouse and a range of apartments, bringing the Castle into line with late sixteenth-century fashion. This work included a tower guest wing on the south edge of the castle court which extended out beyond the inner bailey wall for extra space, and now known as Leicester's building, the subject of this particular programme of tree-ring dating.

Leicester's Building was four floors high and built in a fashionable contemporary Tudor style with "brittle, thin walls and grids of windows" (Fig 2a/b). The building was intended to appear well-proportioned alongside the ancient great tower, one of the reasons for its considerable height, and it set the style for later Elizabethan country house design, especially in the Midlands, with Hardwick Hall being a classic example. The purpose of Robert Dudley's works was to impress Queen Elizabeth I in an effort to persuade her to marry him. She visited the Castle in AD 1566, 1568, and 1572. The full impact of his works, for which no expense was spared, was not seen, however, until the Queen's final visit to Kenilworth in AD 1575, this lasting an unprecedented 19 days, the longest unbroken visit by Her Majesty to any one castle.

Further minor work under Robert Dudley continued at Kenilworth until his death in AD 1588 at which time the Castle passed to his brother Ambrose, the Earl of Warwick.

SAMPLING

A programme of works to install a series of stairs, balconies, and viewing platforms in Leicester's Building was commissioned by English Heritage, the purpose of this being to allow public access to the upper floors of the structure for the first time in over 350 years. These works provided a unique opportunity to safely access the many high-level door and window lintels of the structure (Fig 3a/b), as well as a number of wall timbers, and the surviving timber landings of a lost stair in a corner turret, these being set to the northeast, northwest, and south rooms of the structure (Fig 4).

Given this opportunity, a dendrochronological survey was therefore requested by Jeremy Ashbee (Head Historic Properties Curator, English Heritage), the occasion being taken at this time to obtain tree-ring samples from these timbers in an effort to provide independent evidence of their dates. It is known from historic sources that the building was constructed between AD 1570–72, with alterations made before AD 1575, after which there were no apparent interventions until the Office and Ministry of Works undertook conservation measures in the twentieth century.

Assessment of the timbers, as to their suitability for tree-ring analysis, and subsequent sampling were undertaken in a series of discrete episodes according to appropriate access either from the construction scaffold as installation work progressed, or at the completion of work from the new stairs and viewing platforms. From these accessible timbers a total of 52 samples was thus obtained, the majority of them by coring, though a number was obtained as cross-sectional slices from failed timbers which had been removed during the installation works. Each sample was given the code KNW-D (for Kenilworth site "D") and numbered 01–52. Where possible, the location of each sample was photographed at the time of coring, and/or located on elevations and plans derived from those made and provided by Purcell Miller Tritton Ltd, consulting architects. The sample positions are shown in Figures 5a–d/6a–d. The exception to this was amongst the sliced *ex-situ* timbers where the exact original location of some of the timbers was not always known.

Two core samples, KNW-D05 and KNW-D24, were certainly derived from the same timber (a newly inserted platform providing clearer access to this lintel), and it is likely that one other timber of unknown location within the building is represented by two sliced samples, KNW-D13 and KNW-D18. A small number of timbers remain un-sampled, these clearly being either modern, probably twentieth-century, replacements, or, being derived from very fast grown trees, having too few rings for reliable dating by ring-width dendrochronology.

The programme of dendrochronological analysis reported upon here adds to previous tree-ring analysis undertaken on other parts of the large multi-period Castle complex. These including analysis of timbers from Lord Leicester's Gatehouse (Arnold *et al* 2007a) and Lord Leicester's Stables (Howard *et al* 2006), themselves following still earlier dating of timbers that were removed from Leicester's Stables during repairs in the early AD 1980s, although these timbers were all un-provenanced (Miles 2005a).

ANALYSIS AND RESULTS

Each of the 52 samples obtained from Leicester's Building was prepared by sanding and polishing. It was seen at this time that nine samples had fewer than the 40 rings here deemed necessary for secure dating purposes and they were rejected from this programme of analysis. The annual growth ring widths of the remaining

43 samples were measured, the data of these measurements being given at the end of this report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix 1), this comparative process producing two groups of cross-matching samples.

The first group, comprising nine samples, were combined at their indicated offset positions to form site chronology KNWDSQ01, at a minimum *t*-value of 4.2, with an overall length of 128 rings. Site chronology KNWDSQ01 was then compared to the reference material for oak, cross-matching with a number of these when the date of its first ring is AD 1423 and the date of its last ring is AD 1550. The evidence for this dating is given in Table 2.

The second group, comprising 17 samples, were also combined at their indicated offset positions to form site chronology KNWDSQ02, at a minimum *t*-value of 3.4, this having an overall length of 192 rings. Site chronology KNWDSQ02 was also compared to the corpus of reference material for oak, cross-matching with a number of these when the date of its first ring is AD 1362 and the date of its last ring is AD 1553. The evidence for this dating is given in Table 3.

The two site chronologies thus formed, KNWDSQ01 and KNWDSQ02, were then compared with the 17 remaining measured but ungrouped samples which were also compared individually with the reference data. This indicated cross-matching for only three further samples. The first, KNW-D34, is of 77 rings which were dated as spanning the years AD 1392–1468 (Table 4), the second, KNW-D50, is of 58 rings dated as spanning AD 1473–1530 (Table 5), while the third is KNW-D52, its 65 rings spanning the years AD 1491–1555 (Table 6).

This analysis may be summarised thus:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
KNWDSQ01	9	128	1423–1550
KNWDSQ02	17	192	1362–1553
KNW-D34	1	77	1392–1468
KNW-D50	1	58	1473–1530
KNW-D52	1	65	1491–1555
Ungrouped	14	---	undated
Unmeasured	9	---	---

The relative positions and dates of the 26 constituent samples of the two site chronologies, KNWDSQ01 and KNWDSQ02, and the three individually dated samples, are illustrated in Figure 7.

INTERPRETATION

Analysis by dendrochronology of 43 measured samples from Leicester's Building has produced two dated site chronologies, accounting for 26 samples, and dated a further three samples individually. Interpretation of the sapwood on the dated samples would indicate the that, while a small number of timbers could be of different, earlier dates, the vast majority of them appear to be broadly coeval and to date to the latter half of the sixteenth century.

Individually dated sample KNW-D34

The earliest dated material detected in this programme of analysis appears to be represented by the individually dated sample KNW-D34, a lintel to the first-floor door between the northwest and south rooms. This sample does not retain complete sapwood (the last ring produced by the tree before felling), and it is thus not possible to provide a precise felling date for the timber. The sample does, though, retain the heartwood/sapwood boundary, this being dated to AD 1468. Using the 95% confidence limit of 15–40 rings for the amount of sapwood the tree might have had would give the timber represented an estimated felling date in the range AD 1483–1508.

Individually dated sample KNW-D50

Sample KNW-D50 (a lintel sampled *ex-situ*) has also been dated individually. However, with no heartwood/sapwood boundary it is impossible to say when it was felled, though with a last heartwood ring date of AD 1530, and assuming a minimum of 15 sapwood rings, this is unlikely to have been before AD 1545.

Site chronology KNWDSQ01

None of the samples of site chronology KNWDSQ01 retain complete sapwood and it is not possible to provide a precise felling date for any of the timbers represented. Three samples (KNW-D10, KNW-D16, and KNW-D18), however, retain the heartwood/sapwood boundary (Fig 7), the date of which varies from AD 1544 (KNW-D10 and KNW-D16) to AD 1550 (KNW-D18). Such a small variation in the dates of the heartwood/sapwood transitions in a chronology strongly suggests that these timbers were felled at the same time or at least as part of a single short felling episode. The average date of the heartwood/sapwood boundaries is AD 1546 which, using the same sapwood estimate as above, 15–40 rings, would give the trees represented an estimated felling date in the range AD 1561–86.

It is very likely that a further timber, represented by sample KNW-D13, was also felled during the same period, given that it matches with KNW-D18 with a value of t=12.3 indicating that it is potentially derived from the same tree. It is possible, however, that in this instance, the two samples (both slices) are in fact from the same beam.

The felling date ranges of the timbers represented by the five remaining samples of this group cannot be determined because, in not having the heartwood/sapwood boundary, not only are they missing all their sapwood rings, but, an unknown number of heartwood rings as well. All that may be said is that it is likely that the earliest timber, represented by sample KNW-D26 with a last heartwood ring date of AD 1536, was felled after AD1551, while the latest timbers, represented by samples KNW-D27 and KNW-D30, with a last heartwood ring date of AD 1542, are likely to have been felled after AD 1557 (these dates based on the timbers having a minimum of 15 sapwood rings). However the strong levels of similarity, as indicated by a series of t-values in excess of 5, as well as a further possible same-tree match (t=11.1) between KNW-D27 and KNW-D28, amongst this group of samples forming KNWBSQ01, suggest that all nine timbers are likely to represent a single felling event and hence all be derived from trees felled at the same, or similar, time in a single area of woodland.

In order to attempt to further refine the estimated felling date range for this group of timbers, the material was assessed for its suitability with respect to using the methodology developed by Miles (2005b) and implemented in OxCal v4.4 (Bronk Ramsey 2009; Miles 2006). Following the methodology described by Millard (2002), Bayesian statistical models are used to provide individual sapwood estimates for each timber using the variables of the number of heartwood rings present, the mean ring-width of those heartwood rings, the heartwood/sapwood boundary date, and the number of any surviving sapwood rings (including those that can only be counted, not measured, or those lost on sampling). Miles (2005b) suggests several such models, of which the one that applies to the timbers in this case is that for 'post-Roman England and Wales'. This model is based on data from timbers throughout this area, although there is a bias towards data from Shropshire, Somerset, Hampshire, Oxfordshire, and Kent. This model is considered appropriate geographically for historic timbers from buildings in Warwickshire, as well as being compatible with the growth characteristics of this particular assemblage.

Using the above methodology, we have therefore combined the probability distributions for the felling dates (see Appendix 2) of these three timbers that retain their heartwood/sapwood boundaries, and estimate that this felling episode occurred in *AD 1559–1574* (*95% probability*; *KNWDSQ01felling*; Fig 8), probably in *AD 1562–1570* (*68% probability*). The distributions have good agreement with the interpretation that these timbers represent a single felling episode (Acomb: 140.1, An: 40.8, n: 3).

Site chronology KNWDSQ02

A further group of timbers is represented by the 17 samples of site chronology KNWDSQ02, all these again without complete sapwood. Of these 17 samples, 11 retain the heartwood/sapwood boundary (Fig 7), the date of which varies from AD 1545 (KNW-D04) to AD 1553 (KNW-D38, KNW-D43, and KNW-D46). Such a small variation in the dates of the heartwood/sapwood transitions in a chronology strongly suggests that these timbers were felled at the same time or at least as part of a single short felling episode. The average date of this boundary is AD 1550, very slightly later than the group discussed above. Using the usual sapwood estimate of 15—40 rings would give the trees represented an estimated felling date in the range AD 1565–90.

It is again very likely that a further timber, represented by sample KNW-D17, was also felled during the period AD 1565–90 because, given that it matches a sample (KNW-D06) with a heartwood/sapwood boundary with a value of t=10.1, it is possible that these two timbers have been derived from the same tree.

The felling date ranges of the timbers represented by the five remaining samples of this group cannot be determined because, again, in not having the heartwood/sapwood boundary, they are missing an unknown number of heartwood rings. It is likely that the earliest timber, represented by sample KNW-D23 with a last heartwood ring date of AD 1474, was felled after AD1489, while the latest timber, represented by sample KNW-D21 with a last heartwood ring date of

AD 1541, is likely to have been felled after AD 1556 (these dates again based on the timbers having a minimum of 15 sapwood rings). However, once again, the strong levels of similarity, as indicated by a series of *t*-values in excess of 5, amongst this group of samples forming KNWBSQ02 suggest that all 17 timbers are likely to represent a single felling event and hence all be derived from trees felled at the same, or similar, time in a single area of woodland.

Again in an attempt to further refine the estimated felling date range for this group of timbers, the material was assessed for its suitability with respect to using the methodology described by Millard (2002), developed by Miles (2005b) and implemented in OxCal v4.4 (Bronk Ramsey 2009; Miles 2006). We have therefore combined the probability distributions for the felling dates of these 11 timbers that retain their heartwood/sapwood boundaries, and estimate that this felling episode occurred in *AD 1567–1576* (*95% probability*; *KNWDSQ02felling*; Fig 8), probably in *AD 1568–1573* (*68% probability*). The distributions have good agreement with the interpretation that these timbers represent a single felling episode (Acomb: 141.5, An: 21.3, n: 11).

Individually dated sample KNW-D52

A third individually dated timber (also a lintel sampled *ex situ*) is represented by KNW-D52. This sample is again without complete sapwood, and a precise felling date for the timber cannot be determined. However, with a heartwood/sapwood boundary dated to AD 1555, and using the same sapwood estimate as above (15-40 rings) the timber has an estimated felling date in the range AD 1570–95.

DISCUSSION AND CONCLUSION

All 29 dated samples are illustrated in their relative positions on Figure 10. It may thus be seen that while one timber, represented by sample KNW-D34, is of late-fifteenth/early sixteenth century date, there are a series of samples, 15 in all, that represent timbers having estimated felling dates in the later sixteenth century. The position of the heartwood/sapwood boundary on these later sixteenth-century samples varies by only 11 years from relative position 183 (AD 1544), on samples KNW-D10 and KNW-D16, to relative position 194 (AD 1555), on sample KNW-D52 (Figure 10). Such consistency in the position of the heartwood/sapwood boundary is indicative of a group a timbers having a similar, though not necessarily identical, felling date as they could potential represent a single but short episode of felling.

The overall average date of the heartwood/sapwood boundary on all these later-sixteenth century samples (where it exists) is AD 1549. Using the same sapwood estimate as above would give these timers an estimated felling date in the range AD 1564–89. But using the method described by Millard (2002) above for these 15 samples (see Appendix 2) estimates that this felling episode occurred in *AD 1567–1574* (*95% probability*; *KNWDSQ01S&Q02 + KNW-D52*; Fig 9), probably in *AD 1568–1572* (*68% probability*). The distributions have good agreement with the interpretation that these timbers represent a single felling episode (Acomb: 140.1, An: 18.3, n: 15).

It will be seen that both these estimated felling date ranges neatly bracket the documented construction date of Leicester's Building confirming that a large number of the timbers found here are original and belong with the works undertaken by Robert Dudley in his attempts to woe Queen Elizabeth I. It is probable, furthermore, given that there is no evidence of any other works here until the twentieth century, that those timbers for which a felling date range cannot be given (those that lack the heartwood/sapwood boundary), were also felled as part of Dudley's works, though this of course is not certain. This interpretation of all but one timber (KNW-D34) probably representing a single felling event is, however, supported by the level of cross-matching within the groups of timbers forming site chronologies KNWDSQ01 and KNWDSQ02 (see above).

The clear exception, KNW-D34, appears anomalous. As indicated above, the usual 15–40 sapwood ring estimate produces an estimated felling date for the tree in the range AD 1483–1508, whereas the use of the `Sapwood` function in OxCal, as per above, estimates that the felling of the tree occurred in *AD 1476–1500* (*95% probability*; *KNW-D34*; Fig 11); probably in *AD 1479–1491* (*68% probability*).

Woodland sources

It may be of interest to note that although the two site chronologies created during the analysis of these samples, KNWDSQ01 and KNWDSQ02, share a 128-year overlap with each other, AD 1423–1550, and AD 1362–1553 respectively, they do not cross-match significantly with each other (t=2.6), or with the three individually dated timbers, sufficiently well for all dated samples to be combined into a single site chronology. This might indicate that, although the timbers are of the same date and were felled for the same programme of works, they have been sourced from different woodlands or woodland areas.

This is borne out to some extent by the cross-matching of each site chronology and the three individually dated samples with the reference material. Site chronology KNWDSQ01 (Table 2) for example, cross-matches best with reference data made up from other sites in Warwickshire, despite having been compared with reference chronologies across the British Isles Britain. In particular, site chronology KNWDSQ01 cross-matches very well with material from Lord Leicester's Gatehouse at Kenilworth, itself built in the AD 1570s. Similarly KNW-D50 also cross-matches with reference chronologies from Warwickshire particularly well. This might suggest that these timbers are from a relatively local woodland source.

Site chronology KNWDSQ02 (Table 3), on the other hand, cross-matches with reference data made up from sites with a much greater geographic spread, and with slightly lower t-values. Similarly, samples KNW-D34 and KNW-D52 also cross-match reference data from a wider geographical spread. Perhaps as a consequence of the extensive nature of Robert Dudley's works, some timbers had to be sourced from further afield.

Undated samples

Of the 43 measured samples, 14 remain ungrouped and undated. As may be seen from Table 1, some of these, KNW-D36, KNW-D39, KNW-D47, and KNW-D49, have well over 100 rings, quite enough for reliable dating, while others are shorter, but still of satisfactory length. One or two samples show some possible distortion to their rings, but the majority show no outward signs of any problem. It is common, however, in any programme of analysis to have some samples remaining undated often for no apparent reason. Indeed, given that lintels and assorted wall beams do not always form a cohesive collection of timbers, the fact that just over 67% of measured samples have dated is worthy of note.

REFERENCES

Alcock, N W, Warwick University, Howard, R E, Laxton, R R, and Litton, C D, Nottingham University Tree-ring Dating Laboratory, and Miles, D H, 1991 List 41 no 6 – Leverhulme Cruck Project Results: 1990, *Vernacular Architect*, 22, 45–7

Arnold, A J, and Howard, R E, 2000 *Oliver Cromwell's House, Ely, Cambridgeshire; Tree-ring Analysis of Timbers*, unpubl computer file, *ELYASQ01* Nottingham Tree-ring Dating Laboratory

Arnold, A J, and Howard, R E, 2003 *Little Morton Hall, Cheshire; Tree-ring Analysis of Timbers*, unpubl computer file *LIMHSQ01,* Nottingham Tree-ring Dating Laboratory

Arnold, A J, and Howard, R E, 2006a *Kingsbury Hall, Kingsbury, Warwickshire; Tree-ring Analysis of Timbers*, Centre for Archaeol Rep, 53/2006

Arnold, A J, and Howard, R E, 2007a *Leicester's Gatehouse, Kenilworth Castle, Kenilworth, Warwickshire; Tree-ring Analysis of Timbers*, Centre for Archaeol Rep, 8/2007

Arnold, A J, and Howard, R E, 2007b *Tree-ring Analysis of Timbers from Polesworth Abbey Gatehouse*, Centre for Archaeol Rep, 6/2007

Arnold, A J, and Howard, R E, 2007c *Cromwell Cottage, Cromwell Lane, Tile Hill, Coventry: Tree-ring Analysis of Timbers,* EH Res Dept Rep Ser, 92/2007

Arnold, A J, and Howard, R E, 2008 *Primrose Hill House and Barn, Meadowsweet Avenue, Kings Norton, Birmingham: Tree-ring Analysis of Timbers*, EH Res Dept Rep Series, 41/2008

Arnold, A J, and Howard, R E, 2013a *Tree-ring Analysis of Timbers from Aldeby Hall, Aldeby, Near Beccles, Norfolk*, unpubl computer file *ADBASQ01,* Nottingham Tree-ring Dating Laboratory

Arnold, A J, and Howard, R E, 2013b *New House Farm, Moccas, Herefordshire; Tree-ring Analysis of Timbers*, unpubl computer file *MOCASQ01,* Nottingham Tree-ring Dating Laboratory

Arnold, A J, and Howard, R E, 2013c *Oakham Castle, Oakham, Rutland: Tree-ring Analysis of Timbers,* EHRes Dept Rep Ser, 23/2013

Arnold, A J and Howard, R E, 2014a *Alcester War Memorial Town Hall, Alcester, Warwickshire; Tree-ring Analysis of Timbers*, unpubl computer file *ALCCSQ01,* Nottingham Tree-ring Dating Laboratory

Arnold, A J, and Howard, R E, 2014b *St John's Walk, Hereford Cathedral, Herefordshire; Tree-ring Analysis of Timbers*, unpubl computer file *HERCSQ01,* Nottingham Tree-ring Dating Laboratory

Arnold, A J, Howard, R E, and Litton, C D, 2003 *Tree-ring Analysis of Timbers from Littlebourne Barn, Near Canterbury, Kent*, Centre for Archaeol Rep, 95/2003

Arnold, A J, Howard, R E, Litton, C D, and Dawson, G, 2005 *The Tree-ring Dating of a Number of Bellframes in Leicestershire,* Centre for Archaeol Rep, 5/2005

Arnold, A J, Howard, R E, and Litton, C D, 2006a *Tree-ring Analysis of Samples from Middleton Hall, Middleton, Warwickshire,* EH Res Dep Rep Series, 13/2006

Arnold, A, J, Howard, R E, and Litton C D, 2006b *St Peter's Church, West Molsey, Elmbridge, Surrey: Tree-ring Analysis of Timbers*, Centre for Archaeol Rep, 90/2006

Arnold, A, Howard, R, and Litton, C, 2007 *Leicester's Gatehouse, Kenilworth Castle, Kenilworth, Warwickshire: Tree-ring Analysis of Timbers,* EH Res Dept Rep Series, 8/2007

Arnold, A J, Howard, R E, and Litton, C D, 2008a List 197 nos 26, 27 – Nottingham Tree-ring Dating Laboratory, *Vernacular Architect*, 39, 119–28

Arnold, A J, Howard, R E, and Litton, C D, 2008b – Nottingham Tree-ring Dating Laboratory: additional dendrochronology dates, no 11, *Vernacular Architect*, 39, 107–11

Bridge M, 2001 *Tree-ring analysis of timbers from Priory Barn, Little Wymondley, Hertfordshire*, Centre for Archaeol Rep, 18/2001

Bridge, M and Miles D, 2011 *The Reader's House, Ludlow, Shropshire: Tree-ring Analysis of Timbers*, EH Res Rep Ser, 108/2011

Bronk Ramsey, C, 2009 Bayesian analysis of radiocarbon dates, *Radiocarbon*, 51, 37–60. https://doi.org/10.1017/S0033822200033865

Haddon-Reece, D, Miles, D, and Munby, J, 1990 List 38: Tree-ring dates from the Ancient Monuments Laboratory, *Vernacular Architect*, 21, 46–50

Hillam, J, 1997 *Tree-ring analysis of oak timbers from the Thames Foreshore Project, Greater London*, Anc Mon Lab Rep, 73/1997

Hillam, J, 1980 *Kingscote Street (KSC77) – final tree-ring report*, Anc Mon Lab Rep, 3260

Howard, R E, Laxton, R R, and Litton, C D, 1996 *Tree-ring Analysis of Timbers from Mercer's Hall, Mercer's Lane, Gloucester*, Anc Mon Lab Rep, 13/1996

Howard, R E, Laxton, R R, and Litton, C D, 1997 List 75 no 7a/c 7d - Nottingham University Tree-Ring Dating Laboratory Results: general list, *Vernacular Architect*, 28, 124–27

Howard, R E, Laxton, R R, and Litton, C D, 1998 *Tree-ring Analysis of Timbers from Naas House, Lydney, Gloucestershire,* Anc Mon Lab Rep, 36/1998

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

Howard, R E, Laxton, R R, and Litton, C D, 2000b *Tree-ring Analysis of Timbers from Headstone Manor House, Pinner View, Harrow, London*, Anc Mon Lab Rep, 81/2000

Howard, R E, Litton, C D, and Arnold A J, 2006 *Tree-ring Analysis of Timbers from Lord Leicester's Stables, Kenilworth Castle, Warwickshire*, EH Res Dept Rep Series, 21/2006

Howard, R E, Arnold, A J, and Tyers, C, 2015 *The Bede House, Church Lane, Lyddington, Rutland: Tree-ring Analysis of Oak Timbers*, HE Res Rep Ser, 37/2015

Laxton, R R, Litton, C D, and Simpson, W G, 1984 List 12 no 23 – Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in Eastern and Midland England, *Vernacular Architect*, 15, 65–8

Miles, D W H, 2005a The *Tree-Ring Dating of Lord Leicester's Stables, Kenilworth Castle, Warwickshire,* Centre for Archaeol Rep, 17/2005

Miles, D W H, 2005b New developments in the interpretation of dendrochronology as applied to oak building timbers, unpubl D Phil thesis, Oxon

Miles, D W H, 2006 Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales, *Vernacular Architect,* 37, 84–96

Miles, D W H, Worthington, M J, and Dallimore, J, 1997 List 84: Somerset Dendrochronology Project – phase one, *Vernacular Architect*, 28, 172–4

Millard, A, 2002 A Bayesian approach to sapwood estimates and felling dates in dendrochronology, *Archaeometry*, 44, 137–43. https://doi.org/10.1111/1475-4754.00048

Nayling, N, 2006 Gorcott Hall, Warwickshire: Tree-ring analysis of timbers, EH Res Dept Rep Ser, 54/2006

Tyers, I, 1996a *Tree-ring analysis of six secular buildings from the City of Hereford*, Anc Mon Lab Rep, 17/1996

Tyers, I, 1996b *Tree-ring analysis of timbers from Longport Farmhouse, Kent*, ARCUS Rep, 279

Tyers, I, 1997 *Dendrochronological analysis of timbers from Lower House Farm, Tupsley, near Hereford*, ARCUS Rep, 296

Tyers, I, 2000 *Dendrochronological analysis of timbers from Apple Tree Cottage, Elstead, Surrey*, ARCUS Rep, 561

Tyers, I, 2008a *Hartlebury Castle, near Stourport-on-Severn, Worcestershire: Dendrochronological analysis of oak timbers*, EH Res Dept Rep Ser, 76/2008

Tyers, I, 2008b *Hoarstone Farm, Bewdley, Worcestershire: Dendrochronological analysis of oak timbers*, EH Res Dept Rep Ser, 78/2008

Worthington M J and Miles D W H, 2004 *The tree-ring dating of Cradley Village Hall, Cradley, Herefordshire*, Centre for Archaeol Rep, 10/2004

TABLES

Table 1: Details of tree-ring samples from Leicester's Building, Kenilworth Castle, Warwickshire

Sample number	Sample location	Total rings	Sapwood rings	Mean heartwood ring width (mm)	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	North-west room, 3rd floor						
KNW-D01	Garderobe lintel	nm	---		------	------	------
KNW-D02	West wall, lintel to north window	53	6	3.55	------	------	------
KNW-D03	West wall, lintel to south window	nm	---		------	------	------
KNW-D04	West wall, lintel to middle window	53	h/s	3.06	1493	1545	1545
	North-west room, 2nd floor						
KNW-D05/24	Northeast/northwest room, south door, west lintel	141	h/s	0.94	1410	1550	1550
KNW-D06	Door to north wall, south lintel	174	h/s	1.1	1374	1547	1547
	North-west room, 1st floor						
KNW-D07	West wall, lintel to south window	nm	---		------	------	------
KNW-D08	West wall, lintel to north window	nm	---		------	------	------
KNW-D09	West wall, lintel to middle window	nm	---		------	------	------
KNW-D10	Doorway to east room, lintel	88	h/s	1.47	1457	1544	1544
	South room, 1st floor						
KNW-D11	Horizontal plate to north wall	77	4	1.77	------	------	------
	Additional timbers						
KNW-D12	Timber A (slice)	60	no h/s	2.6	1442	------	1501
KNW-D13	Timber B (slice)	83	no h/s	2.8	1454	------	1536
KNW-D14	Timber C (slice)	nm	---		------	------	------
KNW-D15	Timber D (slice)	54	h/s	3.27	1498	1551	1551
KNW-D16	Timber 8	96	h/s	1.87	1449	1544	1544
KNW-D17	Timber 21	162	no h/s	1.15	1362	------	1523
KNW-D18	Timber unknown (slice)	91	h/s	2.68	1460	1550	1550
	2nd floor						

Sample number	Sample location	Total rings	Sapwood rings	Mean heartwood ring width (mm)	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
KNW-D19	Northeast room, door to north wall, outer lintel	nm	---		------	------	------
KNW-D20	Northeast room, door to north wall, middle lintel	nm	---		------	------	------
KNW-D21	Northwest room, door to north wall, middle lintel	111	no h/s	1.55	1431	------	1541
KNW-D22	Northwest room, door to north wall outer lintel	55	no h/s	1.71	1457	------	1511
KNW-D23	Northeast room, door to north wall, inner lintel	82	no h/s	0.85	1393	------	1474
KNW-D24/05	Northeast/northwest room, south door, west lintel	160	h/s	1.01	1387	1546	1546
KNW-D25	Northeast/northwest room, south door, east lintel	68	h/s	3.53	------	------	------
	1st floor						
KNW-D26	Northeast/northwest room, north door, west lintel	107	no h/s	1.21	1430	------	1536
KNW-D27	Northeast/northwest room, north door, east lintel	90	no h/s	2.33	1453	------	1542
KNW-D28	Northwest room, north (front) door, inner lintel	87	no h/s	2.37	1454	------	1540
	3rd floor						
KNW-D29	Northeast-northwest room door, west lintel	76	no h/s	2.37	1463	------	1538
KNW-D30	Northeast-northwest room door, east lintel	120	no h/s	2.21	1423	-----	1542
KNW-D31	Northwest room, doorway to north wall, inner lintel	59	no h/s	2.96	------	------	------
	1st floor						
KNW-D32	Northwest room, south window, middle lintel	91	no h/s	1.77	1450	------	1540
KNW-D33	Northwest/south room door, south middle lintel	57	h/s	1.27	------	------	------
KNW-D34	Northwest/south room door, south lintel	77	h/s	3.03	1392	1468	1468
KNW-D35	Northwest/south room door, north middle lintel	77	h/s	2.61	1474	1550	1550
	2nd floor						
KNW-D36	Northwest/south room door, south lintel (sliced)	133	no h/s	1.96	------	------	------
	Stair turret						

Sample number	Sample location	Total rings	Sapwood rings	Mean heartwood ring width (mm)	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
KNW-D37	Level 4, lintel 2 (in from walkway)	49	h/s	1.6	1504	1552	1552
KNW-D38	Level 4, lintel 4	53	h/s	1.66	1501	1553	1553
KNW-D39	Level 3, lintel 8	130	no h/s	1.48	------	------	------
KNW-D40	Level 3, lintel 9,	nm	---		------	------	------
	Stair turret						
KNW-D41	Level 2, lintel 1	59	h/s	1.1	------	------	------
KNW-D42	Level 2, lintel 2	86	h/s	0.97	1463	1548	1548
KNW-D43	Level 2, lintel 3	70	h/s	0.78	1484	1553	1553
KNW-D44	Level 1, lintel 1	73	no h/s	0.87	------	------	------
KNW-D45	Level 1, lintel 2	65	no h/s	1.81	------	------	------
KNW-D46	Level 1, lintel 5	52	h/s	1.66	1502	1553	1553
	Ex situ beams						
KNW-D47	*Ex situ* beam 1	151	h/s	1.4	------	------	------
KNW-D48	*Ex situ* beam 1	80	no h/s	1.23	------	------	------
KNW-D49	*Ex situ* beam 1	120	h/s	0.97	------	------	------
KNW-D50	*Ex situ* beam 1	58	no h/s	2.91	1473	------	1530
KNW-D51	*Ex situ* beam 1	55	no h/s	1.41	------	------	------
KNW-D52	*Ex situ* beam 1	65	h/s	1.55	1491	1555	1555

h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured

Table 2: Results of the cross-matching of site chronology KNWDSQ01 and relevant reference chronologies when the first-ring date is AD 1423 and the last-ring date is AD 1550

Reference chronology	Span of chronology	*t*-value	Reference
Leicester's Gatehouse, Kenilworth Castle, Warwickshire	AD 1390–1547	11.3	Arnold and Howard 2007a
Town Hall, Alcester, Warwickshire	AD 1374–1625	9.6	Arnold and Howard 2014a
Priory Barn, Little Wymondley, Hertfordshire	AD 1450–1540	8.3	Bridge 2001
Primrose Hill, Kings Norton, Birmingham	AD 1354–1593	8.0	Arnold and Howard 2008
Hartlebury Castle, Worcestershire	AD 1235–1745	7.9	Tyers 2008a
Kingsbury Hall, Kingsbury, Warwickshire	AD 1391–1564	7.8	Arnold and Howard 2006a
Middleton Hall, Warwickshire	AD 1390–1646	7.7	Arnold *et al* 2006a
Lord Leicester's Stables, Kenilworth, Castle, Warwickshire	AD 1482–1599	7.6	Howard *et al* 2006
Mercer's Hall, Mercer's Lane, Gloucester	AD 1289–1541	7.5	Howard *et al* 1996
Hoarstone Farm, Bewdley, Worcestershire	AD 1350–1617	7.5	Tyers 2008b

Table 3: Results of the cross-matching of site chronology KNWDSQ02 and relevant reference chronologies when the first-ring date is AD 1362 and the last-ring date is AD 1553

Reference chronology	Span of chronology	*t*-value	Reference
Stoneleigh Abbey, Stoneleigh, Warwickshire	AD 1398–1658	7.0	Howard *et al* 2000a
Tamworth Castle, Tamworth, Staffordshire	AD 1445–1567	6.7	Laxton *et al* 1984
Aldeby Hall (barn), Beccles, Norfolk	AD 1422–1608	6.6	Arnold and Howard 2013a
Lord Leicester's Stables, Kenilworth, Castle, Warwickshire	AD 1482–1599	6.2	Howard *et al* 2006
Old Palace Lane, Richmond, London	AD 1358–1584	6.1	Hillam 1997
Church of St Peter, Aston Flamville, Leicestershire	AD 1475–1620	6.0	Arnold *et al* 2005
Littlebourne Barn, Canterbury, Kent	AD 1382–1582	6.0	Arnold *et al* 2003
Cromwell's House, Ely, Cambridgeshire	AD 1480–1611	6.0	Arnold and Howard 2000
Little Morton Hall, Congleton, Cheshire	AD 1377–1562	5.9	Arnold and Howard 2003
New House Farm, Moccas, Herefordshire	AD 1350–1584	5.9	Arnold and Howard 2013b

Table 4: Results of the cross-matching of sample KNW-D34 and relevant reference chronologies when the first-ring date is AD 1392 and the last-ring date is AD 1468

Reference chronology	Span of chronology	*t*-value	Reference
Cradley Village Hall, Herefordshire	AD 1347–1530	9.5	Worthington and Miles 2004
Bede House, Lyddington, Rutland	AD 1245–1494	8.5	Howard *et al* 2015
Nether Hall barn, Huddersfield, Yorkshire	AD 1356–1429	8.3	Arnold *et al* 2008a
Cathedral Barn, Hereford, Herefordshire	AD 1359–1491	8.2	Tyers 1996a
West Molsey, Elmbridge, Surrey	AD 1364–1503	8.1	Arnold *et al* 2006b
Mercer's Hall, Mercer's Lane, Gloucester	AD 1289–1541	8.0	Howard *et al* 1996
St John's Walk, Hereford Cathedral, Herefordshire	AD 1356–1504	8.0	Arnold and Howard 2014b
20 High Street, Bruton, Somerset	AD 1318–1461	7.9	Miles *et al* 1997
Gorcott Hall, Redditch, Warwickshire	AD 1385–1531	7.8	Nayling 2006
Hartlebury Castle, Worcestershire	AD 1235–1745	7.9	Tyers 2008a

Table 5: Results of the cross-matching of sample KNW-D50 and relevant reference chronologies when the first-ring date is AD 1473 and the last-ring date is AD 1530

Reference chronology	Span of chronology	*t*-value	Reference
Gatehouse, Polesworth Abbey, Polesworth, Warwickshire	AD 1446–1582	7.1	Arnold and Howard 2007b
Apple Tree Cottage, Elstead, Surrey	AD 1396–1591	6.6	Tyers 2000
Cromwell Cottage, Coventry, Warwickshire	AD 1345–1575	6.3	Arnold and Howard 2007c
Acton Court, Gloucestershire	AD 1328–1575	6.1	Haddon-Reece *et al* 1990
Stoneleigh Abbey, Stoneleigh, Warwickshire	AD 1398–1658	5.8	Howard *et al* 2000a
Lord Leicester's Stables, Kenilworth Castle, Warwickshire	AD 1354–1532	5.7	Howard *et al* 2006
Middleton Hall, Middleton, Warwickshire	AD 1390–1646	5.6	Arnold *et al* 2006a
Leicester's Gatehouse, Kenilworth Castle, Warwickshire	AD 1390–1547	5.5	Howard *et al* 2007b
15/19 Station Street, Mansfield Woodhouse, Nottinghamshire	AD 1431–1538	5.4	Howard *et al* 1997
Pye Corner, Moulsford, Oxfordshire	AD 1340–1558	5.3	Alcock *et al* 1991

Table 6: Results of the cross-matching of sample KNW-D52 and relevant reference chronologies when the first-ring date is AD 1491 and the last-ring date is AD 1555

Reference chronology	Span of chronology	*t*-value	Reference
Kingscote Street, London	AD 1484–1590	5.6	Hillam 1980
21–25 London Road, Sevenoaks, Kent	AD 1481–1588	5.6	Arnold *et al* 2008b
Longport Farmhouse, Kent	AD 1334–1599	5.6	Tyers 1996b
Lower House Farm, Tupsley, Herefordshire	AD 1425–1613	5.5	Tyers 1997
The Reader's House, Ludlow, Shropshire	AD 1406–1615	5.4	Bridge and Miles 2011
Oakham Castle, Oakham, Rutland	AD 1383–1620	5.2	Arnold and Howard 2013c
Headstone Manor, Harrow, London	AD 1439–1545	5.2	Howard *et al* 2000b
Town Hall, Alcester, Warwickshire	AD 1374–1625	5.2	Arnold and Howard 2014a
Mercer's Hall, Mercer's Lane, Gloucester, Gloucestershire	AD 1289–1541	5.1	Howard *et al* 1996
Naas House, Lydney, Gloucestershire	AD 1373–1568	5.1	Howard *et al* 1998

FIGURES

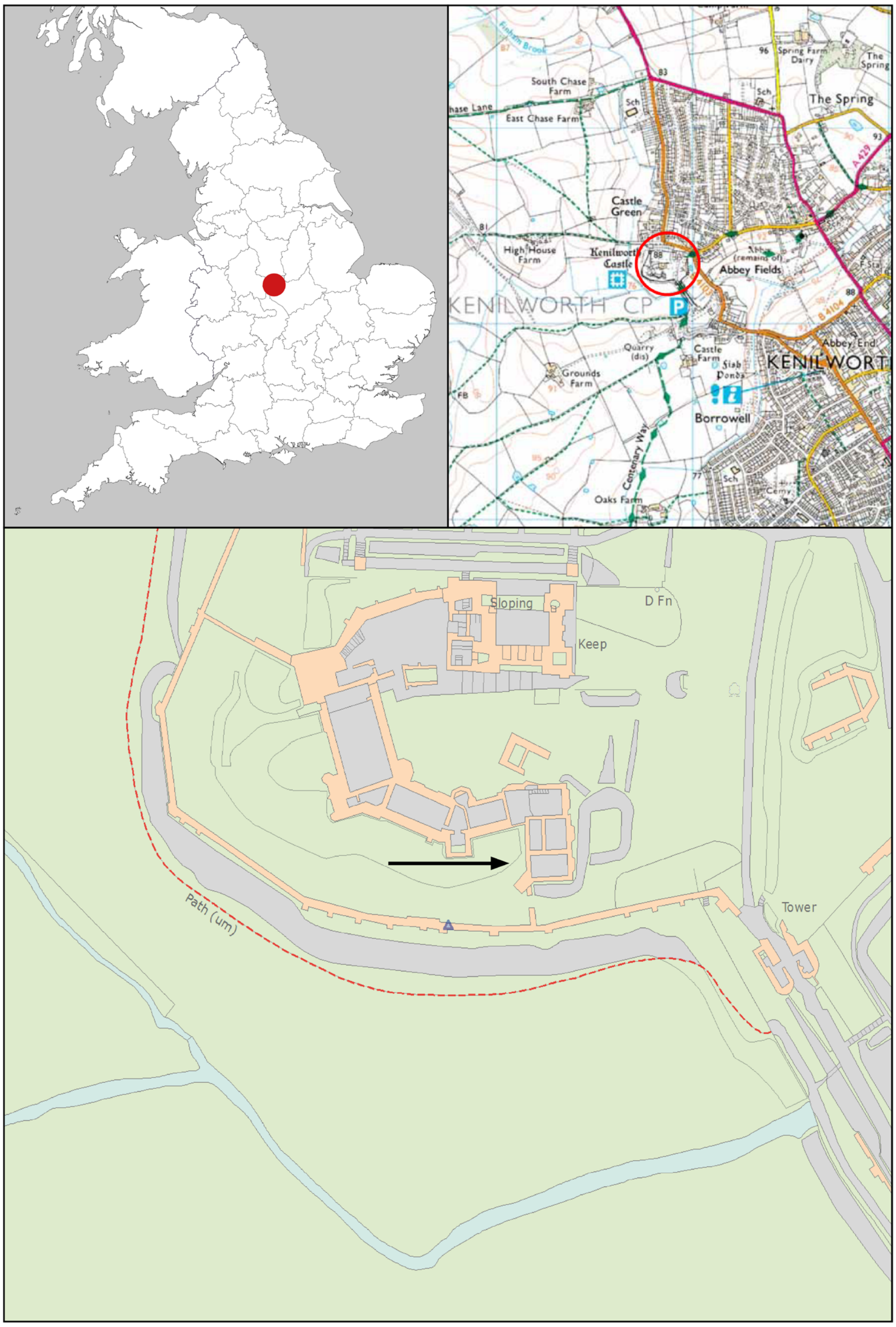


Figure 1: Maps to show the location of Kenilworth (red dot), Kenilworth Castle (circled) and Leicester's Building(arrow). Scale: top right 1:25000; bottom 1:1250. © Crown Copyright and database right 2021. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2021. All rights reserved. Licence number 102006.006. © Historic England

Figure 2a/b: Views of Leicester's Building from the east (top) and the southwest (bottom) (photographs Robert Howard)

Figure 3a/b: Views showing examples of door lintels (photographs Robert Howard)

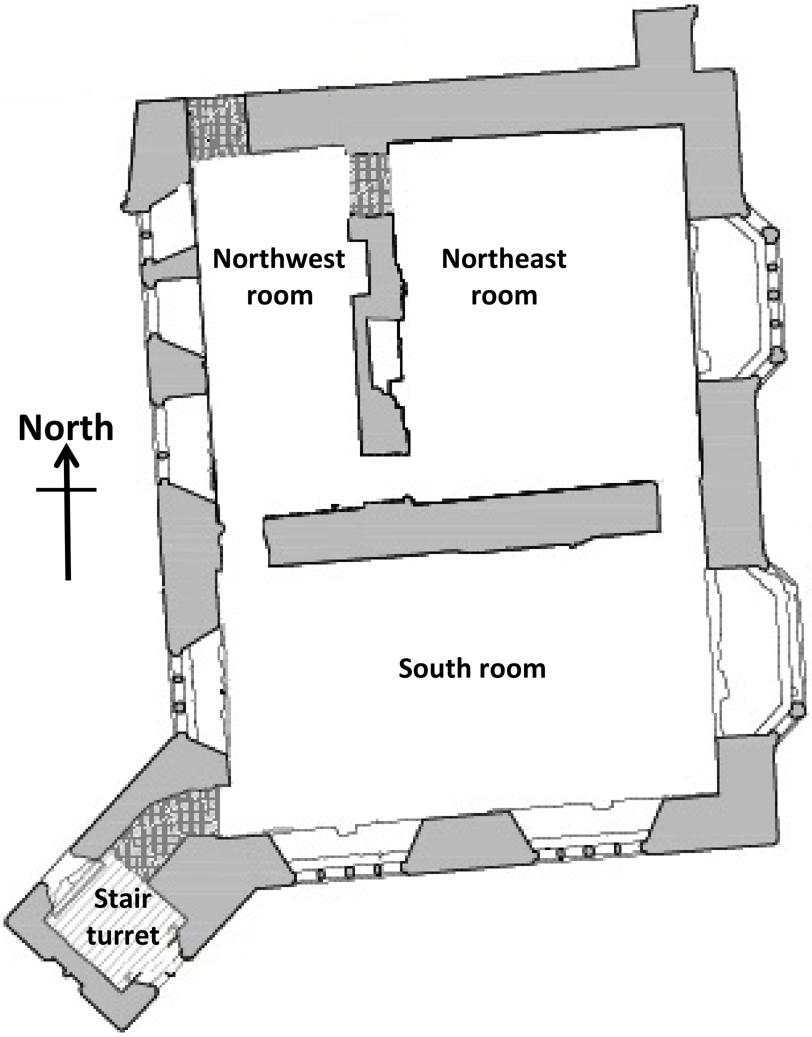


Figure 4: Basic plan of Leicester's Building at ground-floor level to show layout and arrangements of the rooms (after Purcell Miller Tritton)

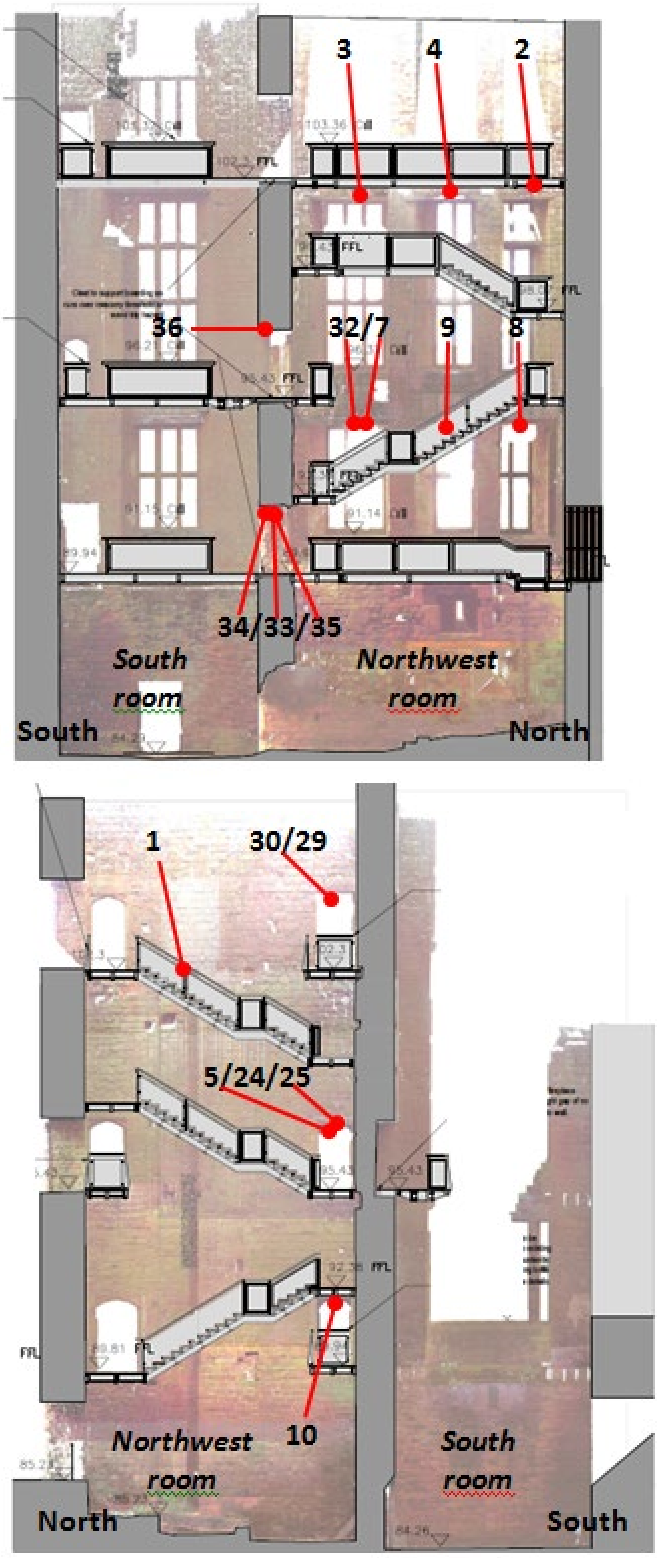


Figure 5a/b: Elevations through the walls to help locate sampled timbers (after Purcell Miller Tritton)

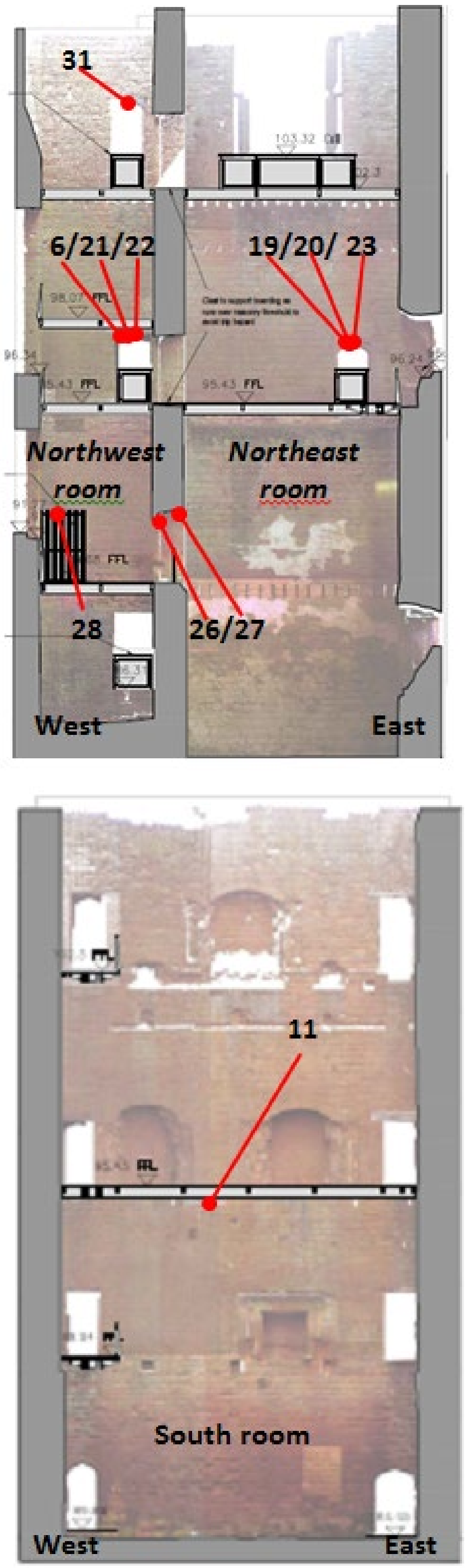


Figure 5c/d: Elevations through the walls to help locate sampled timbers (after Purcell Miller Tritton)

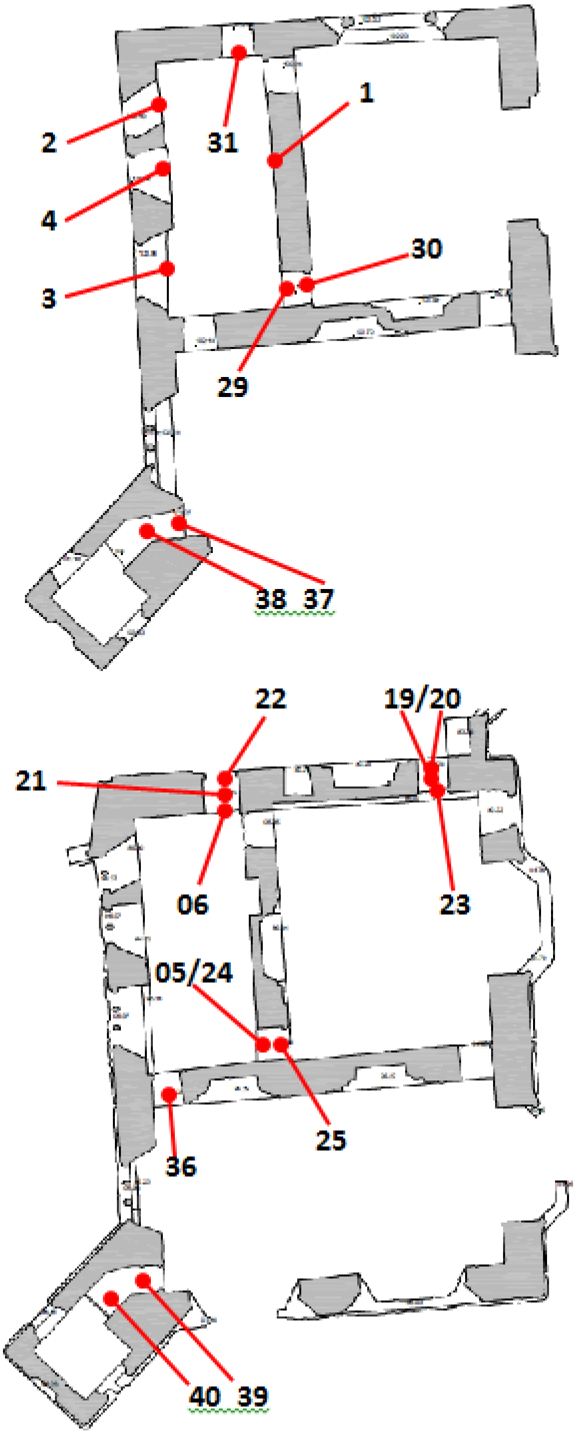


Figure 6a/b: Plans of the building to help locate sampled timbers (after Purcell Miller Tritton)

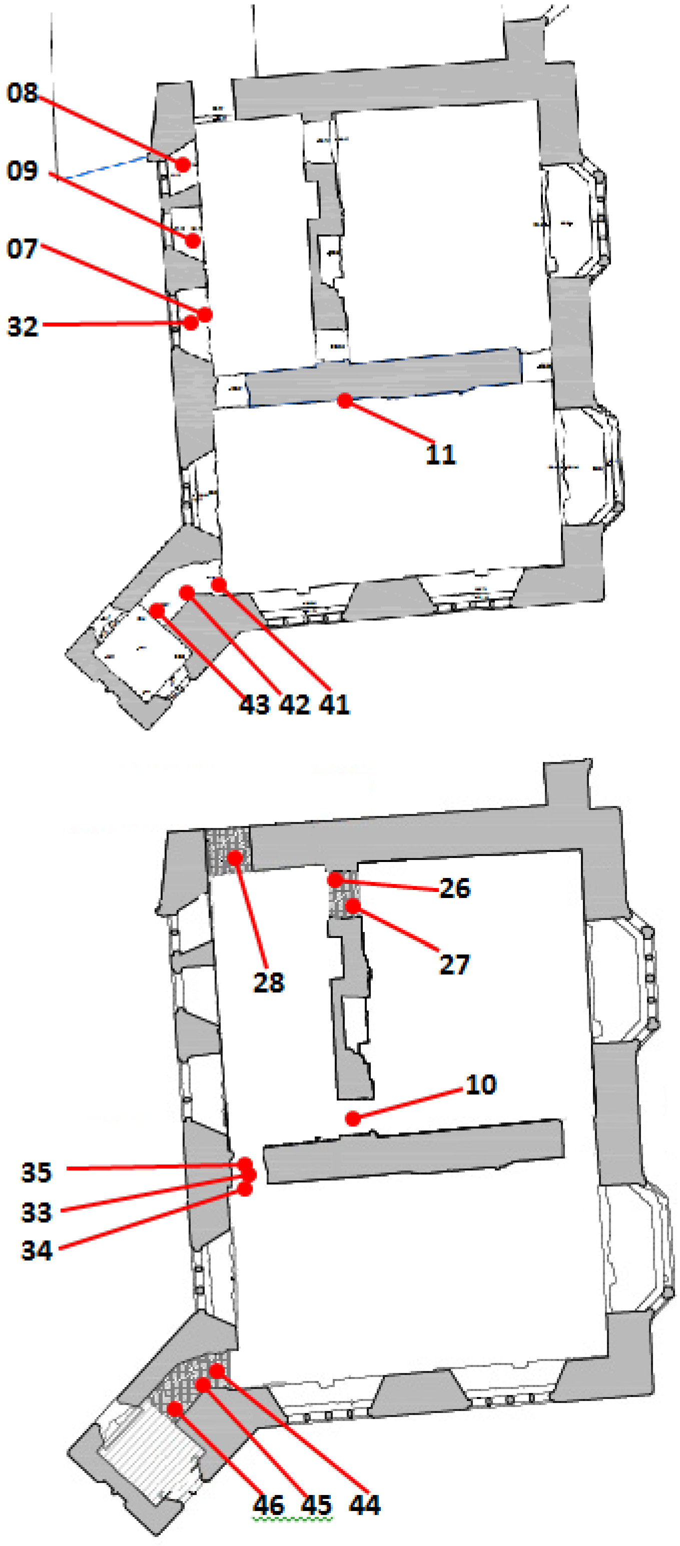
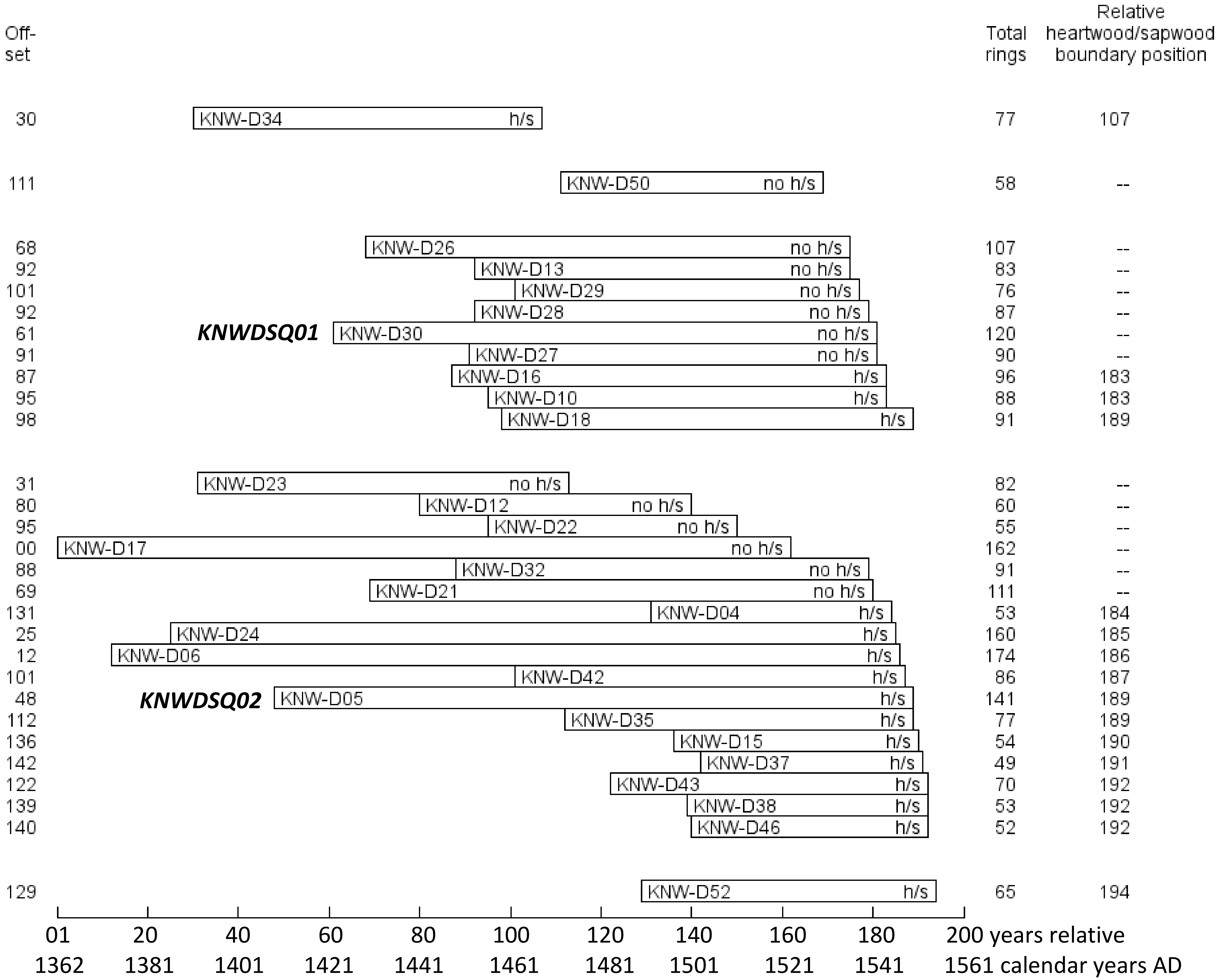


Figure 6c/d: Plans of the building to help locate sampled timbers (after Purcell Miller Tritton)



White bars = heartwood rings; h/s = heartwood/sapwood boundary

Figure 7: Bar diagram of the samples in site chronologies KNWDSQ01 and KNWDSQ02 plus individually dated samples KNW-D34, D50 and D52

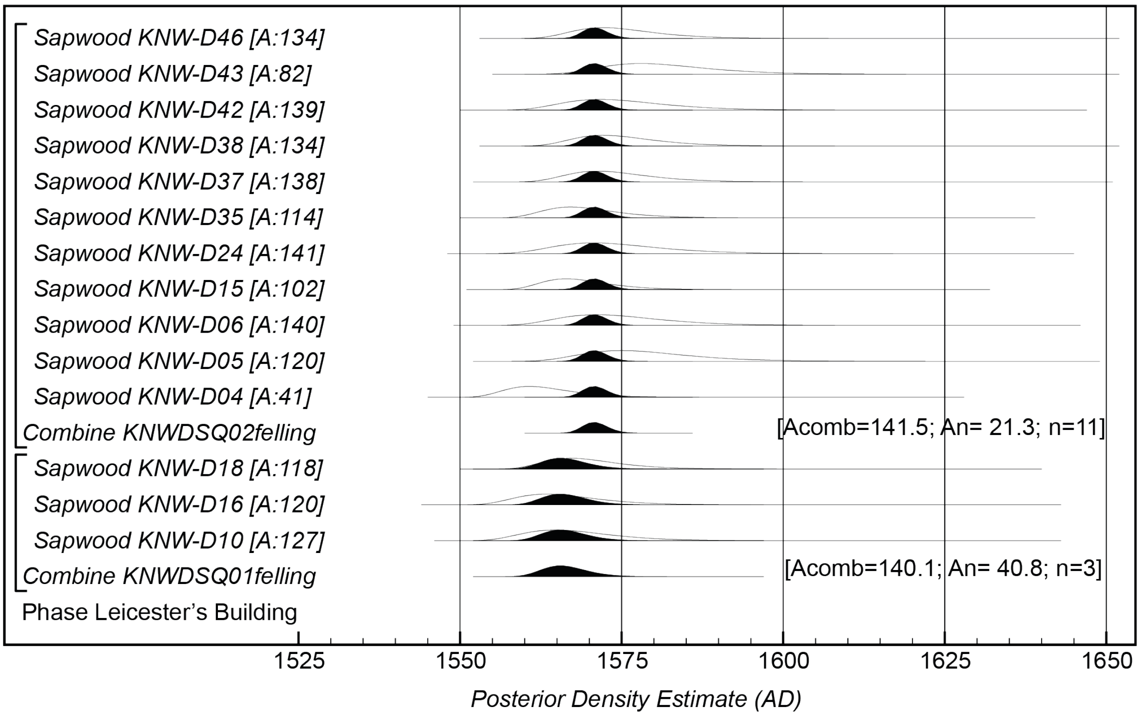


Figure 8: Probability distributions for the date of the associated felling of timbers included in site chronologies KNWDSQ01 and KNWDSQ02

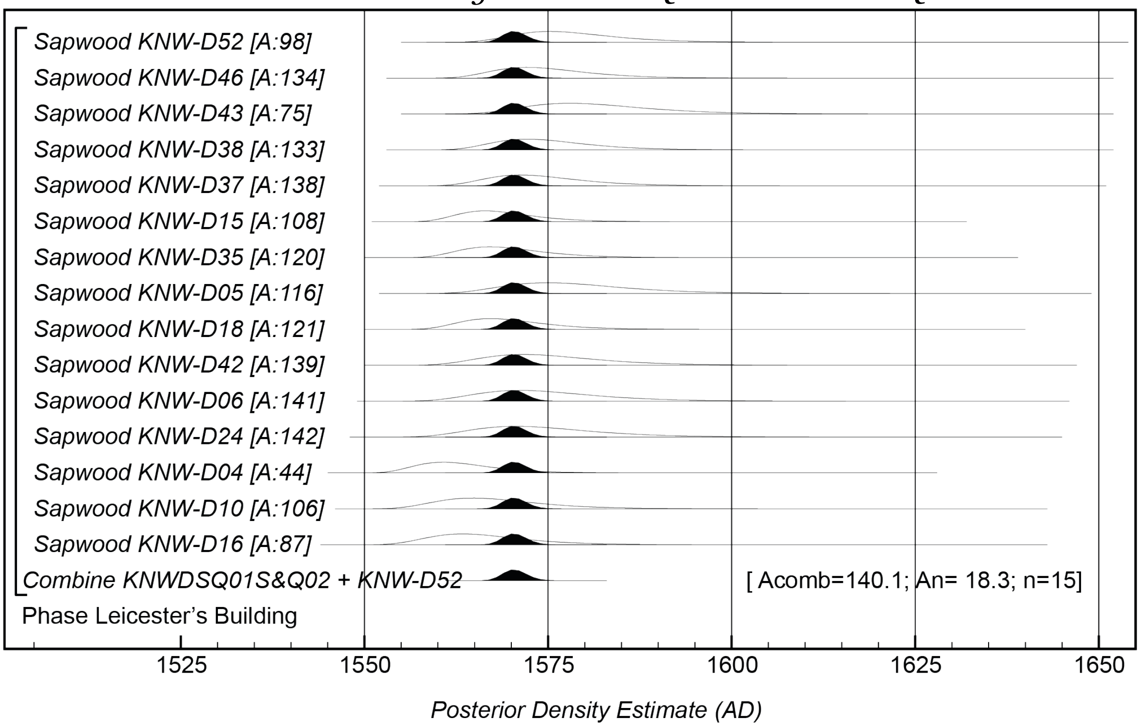
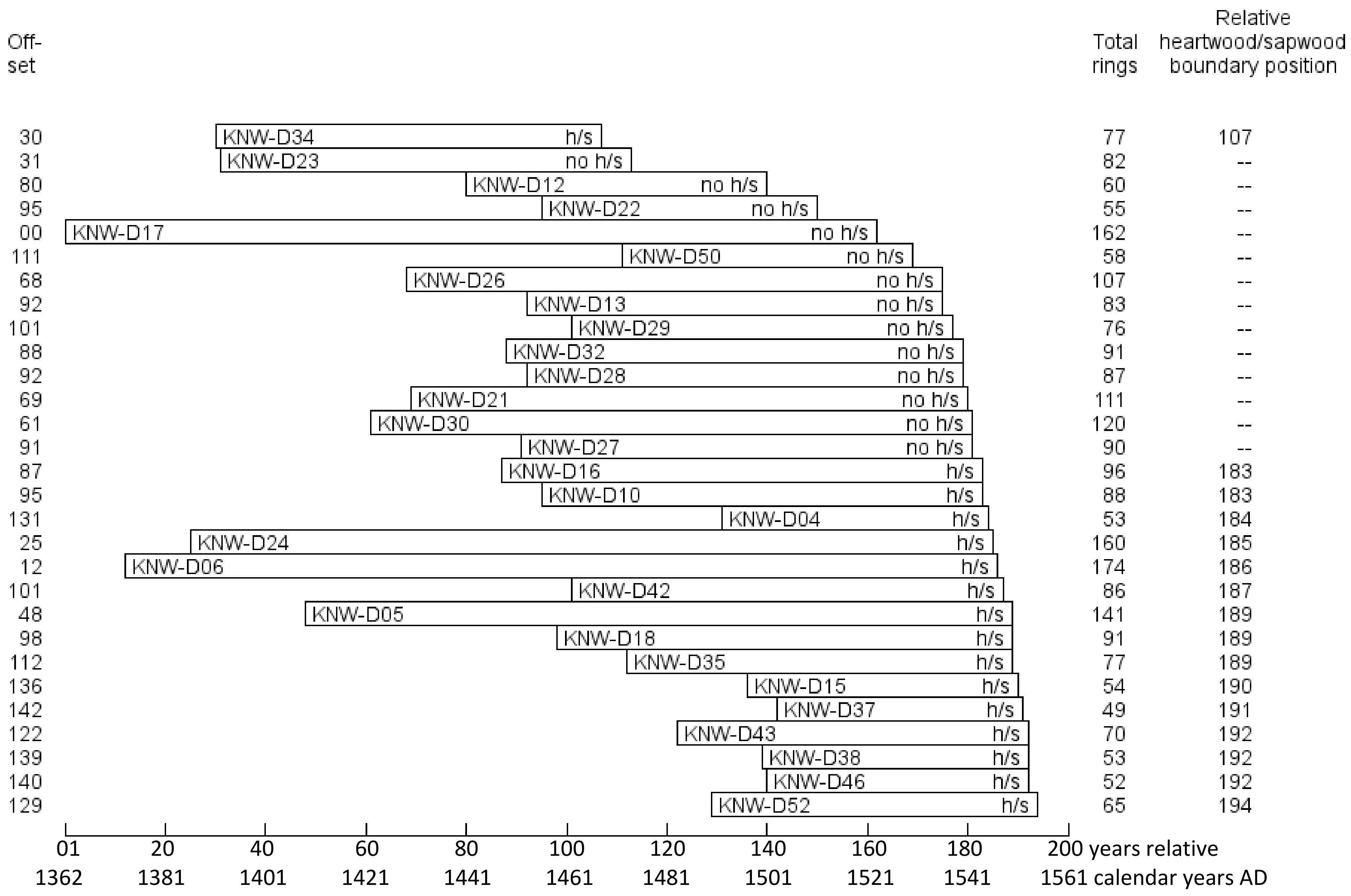


Figure 9: Probability distributions for the date of the associated felling of timbers included in site chronologies KNWDSQ01 and KNWDSQ02 together with individually dated timber KNW-D52



White bars = heartwood rings; h/s = heartwood/sapwood boundary

Figure 10: Bar diagram of all dated samples in last measured ring date order

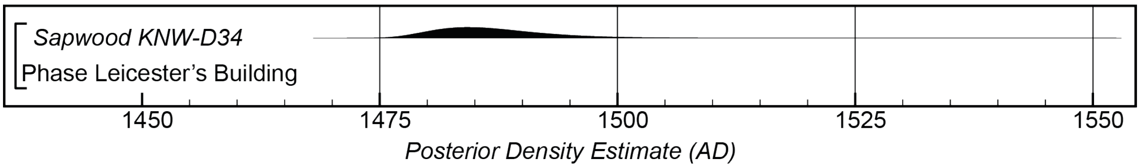


Figure 11: Probability distribution for the estimated felling of the earlier timber, KNW-D34

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

KNW-D02A 53
376 348 412 384 335 316 248 354 580 550 392 318 302 332 572 475 536 390 484 475
438 458 326 293 308 353 273 251 225 212 246 442 364 359 309 336 268 318 331 250
313 284 282 335 240 310 414 559 323 199 159 145 243
KNW-D02B 53
374 352 403 385 339 307 266 347 592 541 396 314 300 333 528 464 539 381 485 480
441 453 332 284 315 387 259 265 204 227 228 435 373 370 302 331 261 313 321 265
312 289 288 334 271 306 411 499 318 194 165 152 258
KNW-D04A 53
260 301 337 388 322 321 518 391 318 371 343 435 308 228 320 275 435 310 325 331
371 354 362 420 345 500 393 295 243 307 200 353 307 271 249 220 219 244 310 226
250 196 309 259 259 359 296 346 212 194 208 146 112
KNW-D04B 53
266 325 341 400 332 316 548 376 323 382 329 428 310 223 328 278 450 318 319 329
364 364 375 386 340 492 376 293 240 320 198 359 314 261 245 243 212 242 320 211
249 212 303 254 251 355 312 353 206 200 198 158 106
KNW-D05A 141
225 196 97 132 110 114 82 115 47 38 36 57 50 71 61 51 42 46 61 85
71 84 101 108 64 83 78 108 92 110 118 92 94 96 68 73 85 75 71 91
78 81 72 78 75 65 69 88 72 53 53 55 72 73 54 64 78 89 110 64
81 75 60 57 66 77 104 75 107 76 86 117 95 95 103 109 107 110 109 98
136 106 115 117 98 142 151 138 161 156 137 164 120 128 101 64 89 73 100 96
79 81 76 75 77 75 67 81 76 117 74 85 122 91 125 89 97 73 118 106
70 131 115 95 95 95 135 123 103 113 125 109 62 131 100 159 110 109 140 149
180
KNW-D05B 141
225 192 104 136 112 106 75 115 39 34 43 58 50 68 61 50 41 43 73 76
59 74 101 101 71 81 69 110 92 115 109 85 102 99 60 71 85 75 82 82
96 75 84 78 85 61 75 94 62 63 49 48 76 67 55 56 67 91 89 67
86 75 60 57 67 82 103 67 106 75 78 132 94 100 100 95 109 117 107 99
140 98 121 117 107 121 162 137 146 160 126 162 135 123 92 71 85 77 90 104
79 90 71 76 80 73 67 84 81 107 91 85 120 85 123 104 98 87 107 103
95 148 107 92 103 95 136 110 85 120 125 112 67 128 99 144 117 124 153 163
182
KNW-D06A 174
194 229 199 192 226 189 173 154 131 180 146 174 160 126 142 112 116 93 90 84
94 103 127 109 125 150 138 118 119 101 104 89 101 89 116 127 160 153 92 127
108 100 61 67 52 46 35 54 46 60 53 36 56 50 53 64 35 46 60 52
50 57 42 82 48 65 75 57 70 68 45 39 55 67 56 51 46 44 48 64
53 48 54 75 51 48 42 39 35 46 45 40 45 58 59 54 43 48 48 45
46 61 113 56 93 53 61 83 72 82 91 75 95 118 98 62 115 72 102 95
81 100 154 149 157 161 127 142 159 143 132 123 137 89 149 136 96 107 97 65
98 100 122 159 130 208 189 185 182 150 178 196 209 174 222 187 199 278 206 190
195 229 259 224 219 193 248 141 116 236 165 325 153 158
KNW-D06B 174
212 226 184 204 221 195 167 159 130 179 151 176 155 130 141 114 110 95 92 83
96 103 125 103 121 148 150 115 117 100 102 88 96 95 110 117 173 150 90 131
107 107 64 65 55 42 36 53 42 64 53 37 50 55 50 64 39 50 56 53
46 57 48 75 56 59 75 60 71 64 51 35 53 65 58 52 50 44 49 56

53 53 68 66 47 51 35 35 45 47 42 48 40 57 53 47 46 55 45 42
50 54 114 57 88 48 67 90 64 79 88 78 95 110 104 68 110 64 103 96
80 95 171 150 160 150 132 137 160 148 126 123 143 85 150 137 100 108 100 63
96 103 112 163 132 200 206 168 190 150 190 181 196 190 212 199 200 274 215 181
193 232 252 231 220 206 222 149 125 256 146 306 140 146
KNW-D10A 88
186 234 192 233 259 270 229 192 276 191 191 214 310 199 203 188 193 229 273 193
157 113 167 162 172 137 135 125 75 110 125 98 128 161 154 100 96 106 86 109
117 134 167 146 160 155 150 135 120 77 70 84 125 118 114 112 108 101 95 94
97 148 134 89 121 117 126 104 103 146 146 142 118 101 150 110 106 109 144 145
110 150 143 125 152 120 129 190
KNW-D10B 88
189 224 196 238 268 261 229 178 310 214 181 212 319 197 199 193 203 253 268 168
173 126 167 176 192 152 157 114 75 110 110 110 122 147 137 103 107 104 95 126
125 137 151 158 171 162 157 129 98 82 77 89 125 107 106 117 117 107 104 93
84 151 127 89 118 126 115 109 115 154 148 127 109 98 156 104 104 112 143 142
101 148 134 121 154 122 112 192
KNW-D11A 77
97 166 142 185 149 167 134 175 167 200 245 147 182 185 198 178 291 232 178 164
242 243 249 223 182 172 167 166 240 178 139 142 157 179 184 188 218 215 189 118
175 121 193 270 264 164 160 175 195 151 218 175 162 117 198 144 206 139 128 109
185 151 128 103 175 229 193 132 119 129 257 162 159 173 208 255 237
KNW-D11B 77
103 176 146 192 152 162 141 162 161 187 248 152 182 179 191 175 299 215 194 182
216 240 234 226 203 182 182 171 270 175 136 128 150 174 182 198 228 228 187 135
171 118 195 259 235 167 161 156 190 170 210 184 148 121 204 153 193 134 139 117
171 146 131 95 159 223 200 135 120 126 253 139 139 202 220 237 221
KNW-D12A 60
103 182 87 58 105 172 176 164 102 88 116 175 170 160 173 258 300 198 275 320
234 204 191 74 47 167 203 200 198 134 181 95 92 179 318 396 520 600 373 414
264 264 269 319 251 342 270 223 354 187 307 300 248 289 539 707 556 592 527 605
KNW-D12B 60
115 175 77 64 114 181 171 200 82 167 112 173 176 132 167 213 257 156 256 312
227 215 196 64 43 187 189 206 196 126 196 97 100 182 307 391 582 595 381 414
265 260 281 342 229 333 292 199 335 197 334 257 251 295 556 703 580 552 528 590
KNW-D13A 83
123 101 117 111 309 320 242 351 384 394 287 426 482 347 339 314 264 282 297 343
421 434 355 271 308 444 364 360 358 446 473 418 367 487 323 352 389 365 357 451
371 352 316 320 271 267 198 220 224 281 246 246 203 180 191 265 267 228 281 228
209 198 223 173 204 201 239 179 205 190 207 203 248 175 200 190 196 272 178 136
154 212 214
KNW-D13B 83
113 105 125 134 300 321 253 348 401 432 289 400 471 399 348 278 278 291 275 350
400 453 350 271 306 440 354 354 346 445 446 434 359 448 278 337 370 347 375 409
399 324 356 328 262 293 209 205 241 265 218 246 225 173 178 257 264 240 293 218
200 206 207 180 192 212 196 210 208 179 225 193 248 162 195 183 219 256 173 160
150 211 212
KNW-D15A 54
408 726 511 609 620 444 439 352 221 396 288 494 335 315 312 335 343 271 295 318
409 365 376 251 356 270 541 408 353 310 295 240 237 369 212 334 211 278 268 162
309 256 261 184 137 150 106 292 218 250 284 268 284 399
KNW-D15B 54
382 725 532 623 659 439 403 358 227 400 296 492 332 326 310 329 335 270 299 325

406 357 381 256 331 279 539 424 354 334 307 237 240 360 203 325 218 281 246 173
309 246 269 185 151 156 107 289 209 243 282 262 281 397
KNW-D16A 96
195 190 207 308 216 182 226 200 257 188 303 393 250 320 259 200 272 230 194 299
217 196 205 201 199 227 273 201 181 153 250 220 260 229 254 222 122 172 176 181
179 189 215 132 192 132 123 168 146 143 184 122 175 195 159 183 134 109 90 126
132 139 132 167 157 135 131 136 150 227 277 136 132 165 150 151 175 175 154 150
140 143 200 116 157 134 159 165 135 160 167 158 162 137 193 175
KNW-D16B 96
238 204 191 318 212 175 225 194 258 184 297 389 268 300 313 198 281 227 178 302
237 187 207 175 210 253 271 179 182 167 254 228 257 239 262 231 123 159 195 182
209 187 192 128 185 160 128 175 191 169 201 135 176 190 157 187 124 114 90 132
143 134 138 164 157 128 134 150 152 210 280 137 128 165 157 141 178 170 167 145
133 152 200 132 141 136 155 162 128 190 184 164 178 150 211 190
KNW-D17A 162
238 263 267 184 198 238 227 238 167 164 141 124 120 141 141 119 132 117 136 105
100 166 105 153 106 127 146 103 101 107 85 96 102 114 136 105 104 142 134 111
138 104 99 117 123 99 127 114 117 115 85 109 97 130 61 116 54 57 37 53
46 76 75 60 53 73 75 96 45 75 78 76 54 62 48 75 64 69 76 76
85 79 59 64 57 65 65 59 57 50 78 57 51 65 67 75 60 64 51 82
62 75 73 73 37 73 70 61 62 53 60 48 46 75 78 73 81 56 80 100
60 70 79 77 94 106 88 75 121 83 88 84 93 116 182 175 179 208 168 190
275 237 203 162 150 99 187 297 211 228 276 212 205 164 182 175 168 228 165 214
211 190
KNW-D17B 162
239 264 270 193 189 243 239 225 173 156 157 110 128 135 138 107 147 135 120 117
85 164 103 164 110 115 153 89 109 96 84 78 116 106 146 110 103 150 128 118
138 98 103 116 125 84 132 117 106 128 88 100 105 131 71 109 70 48 37 59
45 81 75 54 60 66 79 96 53 65 83 82 51 51 60 80 57 81 76 62
76 85 64 65 57 64 62 64 52 54 62 64 54 65 67 78 60 59 51 75
65 82 67 70 45 63 65 70 59 48 58 56 45 76 79 81 68 58 88 92
67 71 83 79 89 109 85 65 120 88 97 84 87 110 179 185 173 218 157 200
271 228 204 156 160 115 218 336 289 263 281 220 198 172 171 178 165 231 165 221
193 196
KNW-D18A 91
197 279 326 426 279 390 516 323 326 310 271 342 346 387 413 507 414 303 328 422
327 383 340 490 506 406 368 429 335 325 345 351 404 437 377 328 412 287 259 301
193 211 237 253 235 217 199 188 167 258 281 229 271 236 233 194 216 160 208 225
223 228 201 175 212 175 200 193 180 168 197 265 165 175 186 201 190 189 249 170
146 183 156 121 126 164 150 130 105 166 168
KNW-D18B 91
200 300 309 409 269 426 487 324 309 307 293 341 360 357 397 484 392 282 340 439
329 385 351 478 507 407 358 423 334 356 365 337 354 425 350 337 378 290 252 307
214 204 234 261 244 242 188 193 181 248 284 231 275 243 226 206 203 162 199 229
221 212 196 179 196 173 228 160 178 162 199 271 150 171 206 213 193 167 225 164
138 200 142 138 120 152 144 118 132 153 172
KNW-D21A 111
150 129 174 192 88 126 111 167 192 167 133 139 137 110 80 97 134 104 125 91
118 106 150 148 119 132 160 143 101 145 138 141 152 107 124 106 128 146 150 125
131 132 126 99 131 178 136 198 162 168 215 148 139 112 175 184 150 138 125 171
107 111 160 170 150 224 335 284 329 263 305 353 232 219 139 134 112 190 201 136
190 190 187 178 122 173 134 231 177 175 152 115 110 133 112 177 162 163 158 125
192 117 115 125 114 166 157 150 157 196 128

KNW-D21B 111
147 132 175 186 94 138 106 163 187 168 131 126 117 107 80 112 144 111 128 92
114 107 155 146 112 128 160 135 113 136 139 147 154 107 121 103 135 135 150 119
139 125 138 103 127 177 132 202 157 178 198 135 146 128 178 192 140 124 125 176
103 114 145 162 150 241 345 298 340 265 308 349 232 215 139 127 125 171 201 137
192 207 191 166 113 162 138 220 188 155 144 115 116 141 103 175 162 165 159 128
187 125 115 125 103 184 153 154 139 230 125
KNW-D22A 55
163 149 96 146 134 127 109 106 88 65 98 119 125 118 95 100 112 101 126 205
221 264 230 196 219 141 146 169 206 187 127 139 130 151 113 143 123 134 145 243
316 309 384 260 284 336 211 231 190 167 140 189 231 150 251
KNW-D22B 55
167 174 96 100 129 120 102 104 81 71 136 125 123 116 90 110 101 96 128 209
210 269 228 198 213 122 149 164 178 193 145 127 137 149 92 146 128 151 159 229
326 298 378 280 276 342 218 243 185 168 123 206 228 129 228
KNW-D23A 82
97 103 100 112 108 121 169 148 134 134 119 100 99 108 81 114 100 155 121 67
125 79 86 53 51 55 37 42 57 58 83 82 58 60 66 81 90 60 76 100
81 59 80 63 107 78 92 122 111 133 111 67 69 121 96 126 110 97 92 105
97 83 96 128 117 75 89 46 33 34 45 34 41 33 36 59 43 59 50 45
50 62
KNW-D23B 82
103 101 92 107 115 112 177 159 128 139 122 88 106 108 82 115 105 148 125 70
113 85 87 50 57 64 33 49 54 58 82 74 55 61 62 71 96 75 80 101
83 56 78 65 107 85 93 132 100 135 114 75 77 110 86 130 110 97 93 101
87 85 96 120 118 78 96 39 39 37 39 32 41 32 42 56 46 57 47 37
51 74
KNW-D24A 160
193 107 114 100 83 105 117 101 126 106 115 149 152 122 148 134 117 103 123 91
119 126 142 157 92 125 110 130 66 104 37 27 28 44 60 89 88 76 50 60
75 71 102 56 87 109 105 64 64 75 103 85 93 95 79 103 75 67 59 87
63 70 85 64 65 64 69 67 67 79 76 72 57 46 64 64 71 64 61 62
100 98 79 89 85 73 73 72 91 127 97 112 93 95 103 73 82 88 82 100
107 115 95 128 84 95 92 89 95 116 110 103 130 123 142 125 98 112 60 100
78 113 136 94 147 141 100 110 114 144 123 148 184 160 175 159 100 139 87 121
88 149 128 93 116 83 81 91 136 146 128 109 134 162 112 58 150 122 334 226
KNW-D24B 160
197 109 106 99 87 104 114 104 125 105 113 152 150 121 141 142 112 105 126 91
117 125 140 163 98 129 121 120 69 99 46 28 25 28 75 82 85 85 59 57
71 85 107 52 98 93 105 64 75 62 109 86 96 107 78 88 77 69 62 82
62 64 71 55 64 67 64 60 71 81 89 65 60 52 68 75 84 60 54 60
101 98 82 90 92 76 68 71 92 121 90 114 84 103 106 73 87 81 82 96
117 114 96 125 82 94 91 92 100 120 98 115 109 113 145 120 114 98 65 107
62 118 129 100 164 140 91 119 102 160 100 139 187 167 178 156 107 137 89 118
93 136 119 93 117 84 84 97 122 153 130 110 141 159 113 68 150 118 328 225
KNW-D25A 68
825 887 503 391 420 378 577 631 544 379 405 456 782 554 554 518 95 196 207 271
325 429 292 378 389 478 416 404 326 229 374 290 312 208 256 275 137 256 237 237
367 292 355 231 211 184 191 305 213 220 243 496 350 229 245 205 338 401 203 219
181 310 309 385 439 457 328 218
KNW-D25B 68
811 877 483 389 432 389 596 593 536 391 410 476 743 554 545 534 92 210 223 263
331 439 281 360 389 462 428 407 322 228 375 290 319 203 262 290 159 225 221 260

387 303 359 237 187 208 189 309 218 225 237 517 393 226 237 216 336 412 196 207
193 300 325 393 466 479 320 233
KNW-D26A 107
202 173 259 173 203 175 161 117 119 96 131 110 114 152 199 143 145 171 155 155
181 176 132 153 184 189 218 178 198 198 181 172 143 158 125 175 192 177 175 131
107 98 98 109 131 159 142 114 120 135 123 162 126 126 114 96 106 139 120 134
125 122 110 92 106 119 106 93 101 98 96 84 90 96 104 79 81 68 71 86
95 87 93 79 84 65 70 79 84 85 76 68 64 51 45 62 66 67 68 65
62 64 56 76 78 102 141
KNW-D26B 107
194 174 258 170 200 178 158 126 119 98 130 110 108 159 194 143 141 164 171 153
184 180 134 146 178 188 219 177 198 199 174 174 142 158 128 171 200 174 178 134
96 106 92 128 134 148 140 118 112 139 139 157 123 121 120 92 97 135 131 131
121 125 98 101 110 112 101 90 95 100 88 86 82 102 108 81 78 71 67 92
90 91 93 86 96 67 67 99 76 89 76 57 65 48 56 68 65 72 70 56
70 56 61 84 79 102 115
KNW-D27A 90
479 629 531 525 517 476 316 367 335 279 246 160 360 293 268 252 257 204 190 168
243 241 420 268 269 280 292 345 301 301 303 306 208 203 268 192 201 267 179 212
202 200 199 249 200 153 231 250 193 207 236 221 150 171 158 178 213 165 192 194
159 168 128 121 135 202 175 103 127 147 143 150 140 197 194 235 149 122 215 135
146 120 188 158 131 145 164 184 166 237
KNW-D27B 90
472 623 532 528 519 489 332 357 317 260 250 160 360 292 264 236 260 208 192 157
248 240 436 254 278 256 279 335 300 315 320 317 207 209 257 195 190 285 178 217
215 195 191 245 205 159 230 257 192 210 246 222 150 172 157 171 209 165 189 203
159 164 121 138 121 209 172 100 134 151 143 145 140 200 202 233 154 133 196 125
146 134 185 159 121 159 171 196 241 260
KNW-D28A 87
597 525 470 396 457 435 474 433 424 513 239 451 406 435 386 410 318 229 221 276
332 518 375 228 253 393 339 409 373 387 314 207 168 262 222 276 268 228 193 263
212 193 239 206 150 194 196 187 171 181 177 146 141 140 161 220 161 149 167 112
162 108 119 85 162 157 67 73 98 95 89 94 115 129 126 106 90 133 72 100
87 165 115 79 104 148 192
KNW-D28B 87
609 521 456 415 465 428 465 442 403 506 254 446 403 420 383 400 343 207 236 309
335 512 350 223 241 391 350 384 381 381 320 204 170 261 223 269 281 220 195 246
220 202 239 205 146 208 190 190 170 179 168 140 155 129 173 210 175 161 180 100
151 109 109 94 165 154 66 78 92 95 90 97 113 133 129 101 95 140 68 100
93 162 110 78 107 131 179
KNW-D29A 76
344 250 207 273 264 245 238 184 180 238 311 272 397 378 189 246 424 299 341 237
403 423 383 354 410 340 390 379 356 428 438 460 309 396 289 257 261 108 125 184
218 193 175 189 138 243 239 238 210 267 183 150 117 173 145 154 152 134 108 129
88 206 157 192 118 131 60 71 144 112 112 134 140 148 181 265
KNW-D29B 76
342 259 216 263 262 240 276 182 176 250 314 253 398 363 210 252 433 284 334 244
378 438 397 379 380 343 395 381 338 485 418 460 322 393 293 254 261 104 123 201
204 212 171 178 138 213 270 242 218 257 165 166 123 173 147 152 157 130 97 127
90 203 190 193 128 103 75 74 131 92 142 123 137 161 176 241
KNW-D30A 120
313 188 334 203 304 258 231 308 318 316 248 204 276 187 246 325 257 302 372 318
306 357 185 346 279 392 287 335 250 157 160 278 323 337 340 317 256 235 204 223

270 142 212 303 273 215 272 264 213 289 235 278 393 337 125 248 284 291 403 402
412 417 382 353 322 290 318 371 276 254 233 225 196 293 215 206 216 131 129 162
137 138 109 121 65 128 133 151 162 159 132 131 138 106 92 131 113 118 96 72
54 78 88 89 112 142 113 107 203 117 60 72 73 90 90 106 100 126 141 192
KNW-D30B 120
290 198 333 203 309 259 236 300 314 293 256 205 272 202 268 339 307 315 353 322
300 387 187 342 273 395 299 330 268 150 159 279 325 354 320 337 246 207 205 208
268 149 204 301 276 226 269 259 221 280 228 286 365 313 150 225 293 283 400 393
428 413 415 349 306 293 314 371 283 237 237 224 187 293 201 225 212 136 124 165
157 129 112 115 64 123 135 158 159 178 118 115 140 121 90 128 122 96 103 80
48 84 83 93 103 147 122 114 210 93 62 73 74 95 94 105 98 131 150 169
KNW-D31A 59
337 375 246 269 375 385 441 422 353 259 233 208 267 257 232 239 278 270 332 435
307 343 457 530 416 350 384 507 335 350 383 310 256 235 205 280 239 239 209 282
203 191 174 171 252 244 337 205 237 268 356 210 240 220 238 228 253 262 406
KNW-D31B 59
293 365 242 272 384 370 439 410 346 247 227 211 277 261 238 247 280 275 332 434
317 335 457 537 409 340 365 494 350 348 415 279 246 232 200 290 231 237 206 279
225 171 171 152 243 256 318 189 246 243 390 218 278 203 226 225 287 236 437
KNW-D32A 91
187 229 192 280 261 209 228 222 195 136 229 226 282 165 128 161 140 179 238 207
169 133 151 134 78 135 178 173 271 219 176 210 107 152 119 128 93 95 76 77
112 70 74 100 83 114 212 295 228 202 159 287 245 185 182 103 112 134 228 187
129 181 254 121 182 156 176 140 199 178 155 133 121 120 184 181 219 194 210 229
202 240 206 196 167 178 203 265 193 251 287
KNW-D32B 91
186 234 193 274 250 210 232 258 192 137 226 239 271 171 136 153 134 186 228 200
170 128 153 132 79 138 178 164 279 220 171 209 110 153 115 123 100 87 82 79
114 72 71 95 84 123 210 284 232 201 154 284 243 192 175 112 110 132 220 201
120 187 226 135 173 157 167 154 196 171 161 134 120 129 175 176 218 196 218 228
201 261 190 193 165 175 221 250 187 260 281
KNW-D33A 57
113 177 221 169 157 179 137 122 150 96 112 107 83 131 109 78 75 115 110 178
92 137 119 147 180 164 178 150 160 118 125 138 164 130 83 121 111 123 97 101
121 112 112 80 95 103 75 106 117 199 133 85 110 110 128 142 118
KNW-D33B 57
115 185 215 167 160 182 134 123 139 108 106 101 89 135 98 88 71 121 107 166
106 142 116 144 192 167 171 147 154 139 96 146 159 140 95 140 132 107 120 64
139 114 121 67 110 102 79 103 103 196 150 85 107 117 129 134 132
KNW-D34A 77
297 289 261 380 450 384 443 549 573 499 408 458 520 384 428 337 495 473 342 292
329 196 232 253 243 296 315 173 367 312 203 317 282 339 234 273 368 336 250 385
428 184 187 335 274 228 232 253 208 312 170 263 337 186 162 253 268 250 245 302
205 250 344 322 321 273 250 278 303 238 178 225 153 241 281 271 295
KNW-D34B 77
240 306 261 364 405 387 432 543 560 492 375 410 487 393 423 348 493 462 360 302
317 196 242 270 245 264 323 175 365 314 199 317 285 326 236 273 375 336 251 371
425 191 180 346 271 225 225 246 193 281 171 255 353 190 157 264 285 244 235 306
193 259 343 303 328 284 264 267 318 231 203 227 158 231 287 278 284
KNW-D35A 77
101 136 96 179 234 203 243 298 313 303 242 280 253 290 253 278 296 241 230 227
346 464 546 423 306 289 351 325 453 454 462 372 229 229 303 385 362 350 390 348
312 301 286 270 296 374 222 181 163 175 209 212 262 271 269 243 234 308 204 228

181 227 229 166 218 193 218 168 124 170 162 160 128 128 142 183 149
KNW-D35B 77
119 126 96 192 227 213 253 285 312 305 248 278 251 293 253 288 316 249 217 239
314 464 563 428 325 289 360 326 442 437 493 365 226 239 298 387 356 384 384 346
310 305 295 270 299 362 228 185 152 179 211 218 262 274 264 239 237 296 218 221
175 243 196 165 218 215 210 178 126 163 159 153 134 127 143 184 141
KNW-D36A 133
405 284 266 241 269 313 379 228 248 348 353 367 239 243 264 296 327 408 402 271
355 239 203 179 157 132 131 204 232 279 358 282 218 215 225 229 363 325 319 251
267 282 292 271 232 187 171 238 185 186 201 249 262 249 240 271 334 281 116 153
202 206 167 182 228 134 146 128 134 131 129 112 129 215 174 241 209 206 193 212
206 197 193 143 131 135 88 131 162 171 128 131 150 148 167 189 140 153 146 134
162 127 75 81 101 121 135 165 99 118 150 165 150 162 147 153 118 87 95 71
90 115 118 150 101 70 118 91 172 164 81 96 128
KNW-D36B 133
390 279 267 242 270 319 370 211 269 339 368 364 240 259 257 292 377 350 400 287
362 246 187 168 154 123 139 196 226 291 361 267 232 214 220 218 365 325 325 254
268 282 300 256 242 184 167 239 200 175 188 263 258 260 221 280 335 268 127 153
181 215 168 179 225 139 152 125 130 126 126 118 128 214 174 241 216 207 187 223
168 186 196 143 137 123 98 134 160 167 134 125 151 151 175 192 131 153 137 134
165 109 71 93 103 117 151 161 96 107 140 143 150 140 156 161 96 89 71 103
139 104 108 153 110 84 75 141 162 122 97 85 138
KNW-D37A 49
326 431 210 218 243 246 271 244 242 200 184 164 169 129 149 165 109 114 120 105
116 106 119 144 145 135 111 175 145 158 139 144 132 135 128 153 154 112 71 125
129 154 143 118 123 133 93 140 139
KNW-D37B 49
356 419 209 217 250 250 303 245 259 190 180 157 164 133 152 167 104 117 114 110
121 114 132 130 140 134 103 187 128 171 131 157 114 137 116 139 155 95 75 120
115 160 139 114 132 135 103 136 140
KNW-D38A 53
292 355 375 370 401 216 194 272 301 235 248 250 270 246 168 189 114 159 139 103
80 105 80 101 112 109 147 121 110 80 164 127 119 114 137 120 145 155 144 142
102 53 112 128 154 93 82 103 112 112 164 109 144
KNW-D38B 53
361 362 367 371 406 214 187 276 316 230 250 239 271 242 171 192 114 149 147 91
95 106 94 96 106 111 147 131 109 100 171 126 128 115 134 118 143 150 148 132
106 45 123 120 153 101 93 95 109 109 139 103 142
KNW-D39A 130
438 293 375 409 382 357 271 364 296 426 453 482 414 343 370 332 407 337 317 289
278 287 201 210 243 203 93 150 118 148 87 137 181 145 84 90 65 138 256 306
134 118 63 92 96 146 142 200 187 175 142 125 96 142 132 117 86 91 148 151
93 115 78 130 110 130 121 78 116 76 79 111 151 149 115 165 143 74 63 56
74 66 119 50 59 81 76 92 93 88 116 67 40 51 60 48 134 106 107 68
81 59 47 56 78 78 68 83 59 68 59 71 78 68 72 62 85 88 62 49
70 77 87 81 87 54 54 82 133 148
KNW-D39B 130
433 296 363 413 388 351 271 368 300 421 444 479 421 335 371 339 413 304 312 290
279 298 190 203 245 185 92 139 101 123 88 135 179 150 84 100 62 137 268 287
137 114 68 92 101 137 152 200 192 181 145 116 94 143 139 114 90 90 153 151
88 117 81 131 107 121 128 64 116 74 87 111 145 145 115 165 134 86 60 64
83 65 113 54 68 68 79 81 102 87 125 61 44 53 43 57 145 96 117 70
86 56 49 50 72 67 50 100 56 66 51 76 96 67 78 72 64 85 79 50

61 106 80 76 101 60 60 72 129 133
KNW-D41A 59
137 119 148 161 134 106 153 153 217 153 134 156 175 187 285 196 162 146 118 74
57 48 69 68 67 55 70 92 99 96 97 99 96 100 100 88 87 130 98 89
75 77 76 88 110 125 121 91 85 107 78 69 74 64 80 96 81 93 95
KNW-D41B 59
122 120 140 165 131 98 150 155 208 184 125 164 155 189 280 198 159 145 117 85
55 50 64 75 62 57 68 92 100 92 93 102 100 96 100 92 97 109 110 85
79 71 71 92 99 116 107 107 75 107 78 67 68 63 82 100 92 88 113
KNW-D42A 86
103 93 101 123 141 114 117 128 105 129 110 85 155 111 100 42 67 81 85 82
89 107 110 94 107 86 100 117 132 146 130 131 150 153 119 136 136 92 70 50
61 101 72 82 49 83 109 72 81 103 96 107 97 128 97 127 124 111 91 107
62 83 86 129 79 78 80 71 90 93 65 66 71 104 84 78 96 84 76 67
87 93 75 87 76 109
KNW-D42B 86
112 93 106 121 134 114 129 129 100 143 115 54 195 104 92 53 61 85 80 87
91 104 111 104 104 85 101 116 134 144 121 136 147 155 105 125 101 88 64 44
57 96 70 49 50 89 117 71 97 106 89 113 94 130 107 119 127 110 103 104
53 83 99 123 79 73 77 76 84 95 68 70 67 101 87 79 96 76 95 67
87 89 74 86 75 109
KNW-D43A 70
78 62 76 52 49 59 84 82 86 62 91 121 133 76 104 113 75 58 24 33
52 40 37 37 53 67 46 75 86 63 96 60 96 58 96 83 100 79 93 66
85 78 80 79 79 77 67 107 71 63 64 82 103 85 81 109 167 138 78 103
96 117 86 103 125 105 63 32 37 25
KNW-D43B 70
76 64 75 58 43 69 75 75 97 67 79 116 125 91 93 110 73 59 28 30
46 41 34 41 55 55 50 73 73 57 88 64 98 46 96 87 97 75 99 61
88 80 82 70 87 82 67 107 74 50 78 74 108 92 79 95 157 150 67 115
92 109 87 100 131 104 43 37 46 31
KNW-D44A 73
61 65 119 144 175 189 121 101 80 141 139 104 113 146 98 115 104 76 88 71
76 113 111 98 98 102 68 67 78 76 69 76 115 110 122 96 89 171 221 133
70 95 110 125 131 67 47 56 53 42 50 41 32 35 36 42 46 46 45 39
75 53 71 82 86 67 50 46 32 35 55 67 91
KNW-D44B 73
55 58 109 124 186 192 109 103 79 120 146 101 112 147 97 115 107 73 89 73
79 112 107 107 104 101 62 70 73 67 90 84 96 117 132 89 78 160 207 121
95 117 122 125 132 78 53 51 62 61 48 40 32 32 37 48 49 45 42 37
77 59 70 81 109 58 43 45 30 38 55 78 90
KNW-D45A 65
212 207 221 178 173 118 158 166 168 202 140 214 208 167 143 159 170 225 194 217
260 235 192 189 207 232 313 201 160 212 197 202 195 180 192 146 179 165 237 171
149 192 221 164 200 133 118 167 188 168 129 115 133 107 135 143 172 218 144 133
171 226 140 142 196
KNW-D45B 65
231 205 217 182 179 149 160 151 185 203 151 203 216 181 132 160 162 214 203 222
261 218 182 194 215 229 282 203 160 220 187 203 206 171 190 150 170 204 218 161
153 193 214 166 201 131 123 187 204 181 117 133 128 110 129 156 186 211 139 151
195 220 123 152 184
KNW-D46A 52
202 137 114 87 108 121 175 246 171 219 254 157 145 115 138 139 197 197 135 116

117 146 123 160 189 314 220 153 240 343 196 201 142 242 191 191 253 217 209 175
154 118 96 159 87 101 109 124 105 156 135 191
KNW-D46B 52
162 134 124 72 107 117 193 217 186 217 249 162 148 114 128 151 196 192 130 124
119 142 132 167 200 303 228 149 250 314 171 189 153 235 214 185 262 204 217 159
173 120 103 167 76 92 107 115 98 132 131 179
KNW-D47A 151
246 280 359 373 295 323 382 326 254 314 232 246 403 185 204 121 237 141 185 242
281 264 225 264 185 181 182 202 132 181 243 112 110 222 185 217 122 169 135 159
137 170 189 137 131 179 158 179 165 187 178 171 162 220 225 221 188 153 160 207
185 151 115 121 143 89 157 90 199 109 112 117 64 45 62 62 53 53 73 68
71 71 68 56 61 81 68 90 90 80 62 68 90 96 71 53 54 46 59 71
41 60 47 34 43 30 53 52 34 62 59 55 67 37 66 82 80 93 78 62
94 74 69 88 111 121 134 116 140 181 100 124 156 158 132 131 163 178 150 150
115 110 84 106 123 96 153 122 114 134 153
KNW-D47B 151
250 280 354 365 293 322 378 328 258 318 249 235 426 235 263 126 216 137 150 217
288 236 216 272 207 175 195 190 131 168 235 110 104 206 190 237 104 184 154 162
151 165 203 134 134 168 167 194 151 226 178 182 141 193 242 220 193 154 160 228
181 165 99 119 155 87 169 86 219 106 117 120 65 48 76 55 43 53 77 65
69 59 71 53 63 80 68 80 87 82 56 68 87 96 78 58 51 64 50 56
49 56 48 37 43 36 53 46 37 56 62 62 65 38 61 81 84 87 71 71
89 83 79 82 117 113 133 115 140 178 103 128 168 155 134 124 171 172 156 135
121 99 90 95 114 103 156 158 110 132 150
KNW-D48A 80
159 74 101 110 104 147 119 197 232 347 275 253 252 159 180 185 259 198 151 202
136 122 103 124 107 96 61 95 93 122 140 91 111 100 103 75 117 122 85 121
101 107 106 91 135 91 85 95 101 115 112 95 132 113 142 110 106 78 101 107
79 140 100 148 107 100 98 98 109 95 83 82 76 95 74 64 67 76 83 75
KNW-D48B 80
156 80 99 108 100 138 131 196 225 351 285 262 246 171 180 201 248 196 158 208
129 118 100 125 107 95 67 87 99 100 150 96 103 97 104 75 119 125 89 132
100 107 107 103 125 92 93 111 110 115 110 101 129 131 133 113 108 90 100 109
105 175 93 146 110 104 101 104 98 98 71 82 85 80 73 64 64 77 83 73
KNW-D49A 120
220 228 160 179 176 132 146 130 149 91 102 86 72 120 112 85 117 120 176 208
250 240 296 232 182 207 230 261 195 139 128 107 97 78 71 83 101 73 100 69
99 139 75 109 65 73 70 74 75 73 93 75 73 81 76 101 81 76 60 78
75 78 76 84 82 92 84 73 62 62 85 73 82 114 106 84 84 92 67 87
84 85 70 65 79 72 50 71 67 69 73 65 64 75 78 87 84 90 50 65
62 84 82 54 48 40 44 66 72 54 53 45 43 46 45 69 41 39 30 38
KNW-D49B 120
218 205 166 184 184 130 154 125 156 112 92 87 76 119 124 85 130 109 196 200
239 250 283 224 164 220 195 226 190 146 127 102 93 76 75 98 96 78 101 67
92 123 83 100 76 70 79 75 85 68 90 75 67 78 76 91 65 75 56 88
68 78 73 89 84 94 80 70 74 65 78 70 88 123 103 80 84 95 60 82
93 79 73 71 71 72 53 74 64 73 65 84 54 70 81 81 82 91 61 57
75 76 85 62 46 42 48 65 68 67 58 51 43 43 43 56 45 60 53 34
KNW-D50A 58
213 168 479 482 165 206 191 158 194 212 209 206 170 178 280 273 247 311 252 295
300 342 332 339 279 178 190 171 212 129 225 248 246 306 439 398 514 371 366 425
264 170 137 142 209 237 319 184 165 235 312 437 321 674 618 660 526 414
KNW-D50B 58

213 167 467 467 169 207 194 142 197 198 201 226 164 189 267 301 235 335 263 261
320 304 361 347 273 187 190 154 181 142 257 244 265 334 469 496 565 353 359 414
284 188 131 142 181 231 312 171 164 255 281 453 401 521 483 640 530 399
KNW-D51A 55
355 276 305 222 214 266 200 167 166 136 96 67 85 86 70 75 87 119 100 110
132 143 185 128 160 184 142 157 203 239 200 206 157 157 187 148 159 136 162 124
112 85 82 100 110 127 84 75 64 70 48 61 67 60 101
KNW-D51B 55
345 286 312 217 207 270 212 161 174 141 73 68 85 82 70 76 91 121 103 105
130 152 190 121 157 183 142 157 218 242 199 203 156 157 190 149 163 139 166 131
117 92 73 100 121 121 89 78 63 57 50 66 60 78 104
KNW-D52A 65
180 161 210 254 223 253 258 247 325 383 288 306 246 189 257 225 171 142 145 117
128 125 109 154 139 107 125 181 189 149 225 182 167 170 131 180 184 176 125 108
195 109 114 145 196 163 110 106 104 118 145 116 117 71 56 54 55 70 59 62
71 76 89 101 128
KNW-D52B 65
190 185 229 246 219 240 267 234 285 301 221 309 275 202 263 203 154 130 144 103
125 121 106 160 132 92 97 168 190 115 250 170 146 149 123 182 173 179 104 98
178 100 114 159 214 164 110 108 102 117 150 120 115 74 56 57 43 73 65 63
65 78 100 110 132

APPENDIX 1: 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 Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). 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 Figure 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 nine 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 AD 1500, say, then the estimated felling-date range for the tree from which it came originally would be between AD 1506 and AD 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– 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– 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 AD 1506 and AD 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 9–36 (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– 15 rings in this case. By adding on 12– 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– 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 AD 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 complement of, say, 15–35 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*

As 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 882–1981. 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 standardised before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after AD 1810 is very apparent as is the smaller later growth from about AD 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in AD 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two-corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

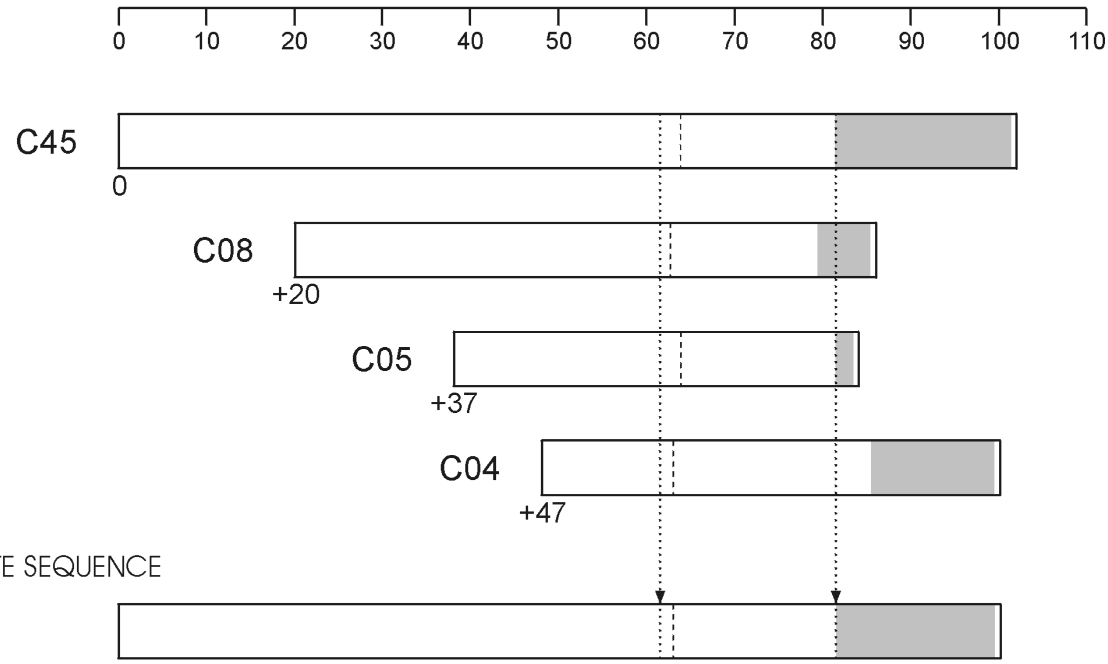


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

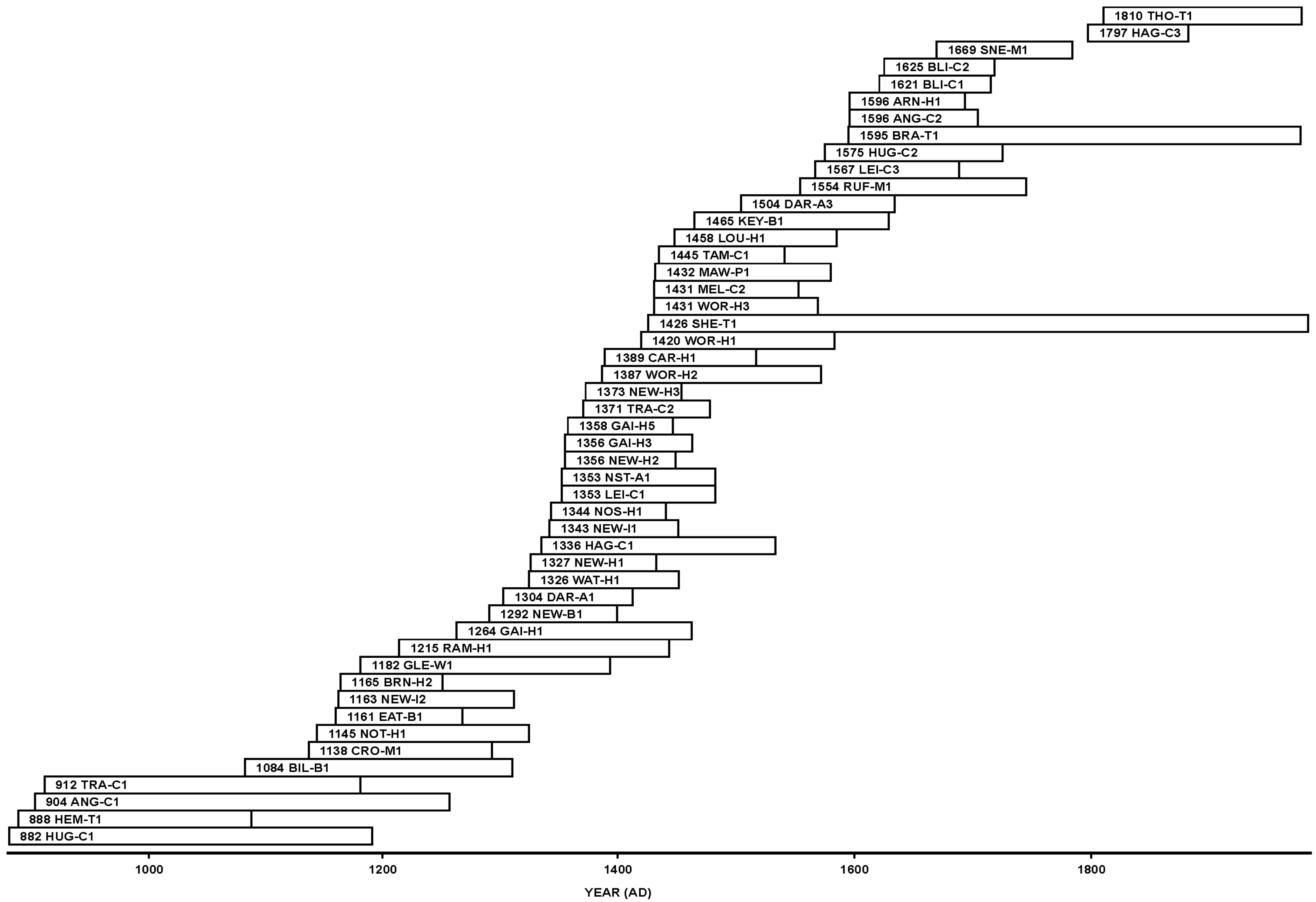
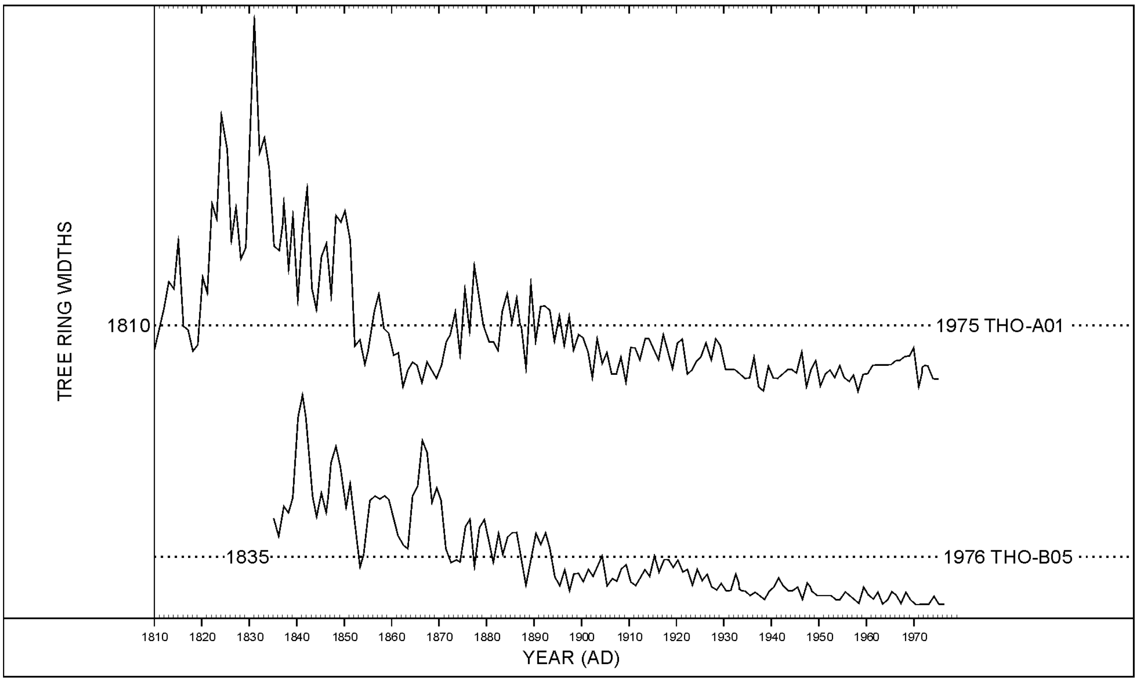


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

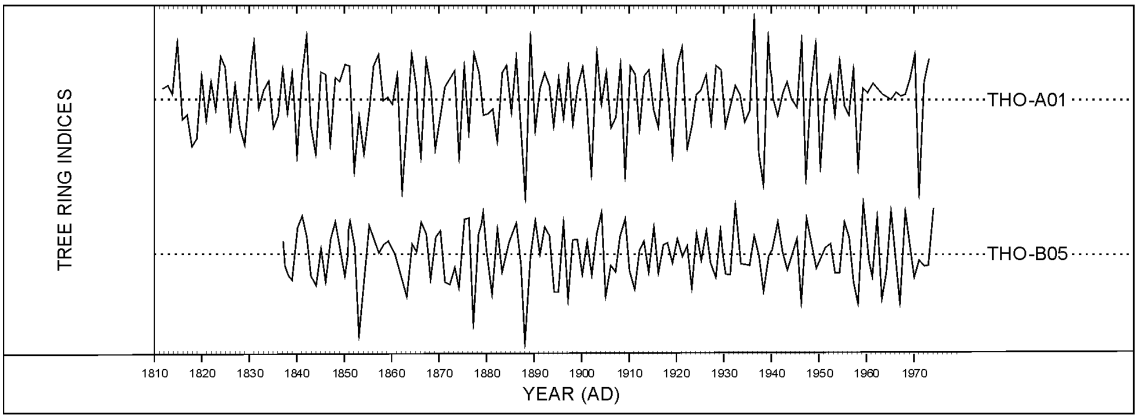


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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

Hughes, M K, Milson, S J, and Legett, P A, 1981 Sapwood estimates in the interpretation of tree-ring dates, *J Archaeol Sci*, 8, 381–90

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *PACT*, 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

APPENDIX 2 OXCAL CODE

KNWDSQ01 and KNWDSQ02 (Fig 8)

```
Options()
 {
  Resolution=1;
 };
 Plot()
 {
  Sapwood_Model("EnglandWales", 2.877146, 0.0838962, -0.3208009,
0.3095663);
  Phase("Leicester's Building");
  Combine("KNWDSQ01")
  {
   Sapwood("KNW-D10", 1544, 88, 0, 1.47);
   Sapwood("KNW-D16", 1544, 96, 0, 1.87);
   Sapwood("KNW-D18", 1550, 91, 0, 2.68);
  };
  Combine("KNWDSQ02")
  {
   Sapwood("KNW-D04", 1545, 53, 0, 3.06);
   Sapwood("KNW-D05", 1550, 141, 0, 0.94);
   Sapwood("KNW-D06", 1547, 174, 0, 1.10);
   Sapwood("KNW-D15", 1551, 54, 0, 3.27);
   Sapwood("KNW-D24", 1546, 160, 0, 1.01);
   Sapwood("KNW-D35", 1550, 77, 0, 2.61);
   Sapwood("KNW-D37", 1552, 49, 0, 1.60);
   Sapwood("KNW-D38", 1553, 53, 0, 1.66);
   Sapwood("KNW-D42", 1548, 86, 0, 0.97);
   Sapwood("KNW-D43", 1553, 70, 0, 0.78);
   Sapwood("KNW-D46", 1553, 52, 0, 1.66);
  };
 };
```

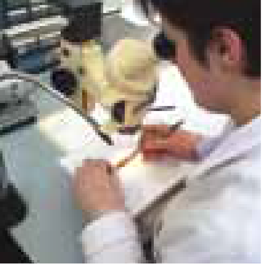
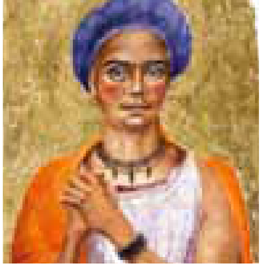
KNWDSQ01 and KNWDSQ02 + KNW-D52 (Fig 9)

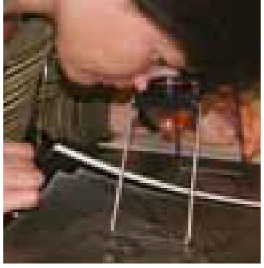
```
Options()
 {
  Resolution=1;
 };
 Plot()
 {
Sapwood_Model("EnglandWales", 2.877146, 0.0838962, -0.3208009,
0.3095663);
  Phase("Leicester's Building");
  Combine("KNWDSQ01S&Q02 + KNW-D52")
  {
   Sapwood("KNW-D16", 1544, 96, 0, 1.87);
```

```
  Sapwood("KNW-D10", 1544, 88, 0, 1.47);
  Sapwood("KNW-D04", 1545, 53, 0, 3.06);
  Sapwood("KNW-D24", 1546, 160, 0, 1.01);
  Sapwood("KNW-D06", 1547, 174, 0, 1.10);
  Sapwood("KNW-D42", 1548, 86, 0, 0.97);
  Sapwood("KNW-D18", 1550, 91, 0, 2.68);
  Sapwood("KNW-D05", 1550, 141, 0, 0.94);
  Sapwood("KNW-D35", 1550, 77, 0, 2.61);
  Sapwood("KNW-D15", 1551, 54, 0, 3.27);
  Sapwood("KNW-D37", 1552, 49, 0, 1.60);
  Sapwood("KNW-D38", 1553, 53, 0, 1.66);
  Sapwood("KNW-D43", 1553, 70, 0, 0.78);
  Sapwood("KNW-D46", 1553, 52, 0, 1.66);
  Sapwood("KNW-D52", 1555, 55, 0, 1.41);
 };
};
```

KNW-D34 (Fig 11)

```
Options()
 {
  Resolution=1;
 };
 Plot()
 {
  Sapwood_Model("EnglandWales", 2.877146, 0.0838962, -0.3208009,
0.3095663);
  Phase("Leicester's Building ")
  {
   Sapwood("KNW-D34", 1468, 77, 0, 3.03);
  };
 };
```


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 English Heritage 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 Reports' database replaces the former:

Ancient Monuments Laboratory (AML) Reports Series
The Centre for Archaeology (CfA) Reports Series
The Archaeological Investigation Report Series and
The Architectural Investigation Reports Series.

ISSN 2059-4453 (Online)