RESEARCH REPORT SERIES no. 23-2014

# GROBY OLD HALL, MARKFIELD ROAD, GROBY, LEICESTERSHIRE
# TREE-RING ANALYSIS OF TIMBERS

## SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION AND ANALYSIS

ENGLISH HERITAGE

*This report has been prepared for use on the internet and the images within it have been down-sampled to optimise downloading and printing speeds.*

*Please note that as a result of this down-sampling the images are not of the highest quality and some of the fine detail may be lost. Any person wishing to obtain a high resolution copy of this report should refer to the ordering information on the following page.*

Research Report Series 23-2014

# GROBY OLD HALL, MARKFIELD ROAD, GROBY, LEICESTERSHIRE

# TREE-RING ANALYSIS OF TIMBERS

Alison Arnold and Robert Howard

NGR: SK 5239 0757



ISSN 2046-9799 (Print)
ISSN 2046-9802 (Online)

*The Research Report Series incorporates reports by the expert teams within the Investigation & Analysis Division of the Heritage Protection Department of English Heritage, alongside contributions from other parts of the organisation. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series.*

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

*Requests for further hard copies, after the initial print run, can be made by emailing:*
*Res.reports@english-heritage.org.uk*
*or by writing to:*
*English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD*
*Please note that a charge will be made to cover printing and postage.*

SUMMARY
Dendrochronological analysis undertaken on samples from within this complex building resulted in the construction of two site sequences, only one of which could be dated. Site sequence GROBSQ01 contains 45 samples and spans the period AD 1321–1516. Two further samples were individually dated to AD 1400–62 and AD 1577–1668.

The dated samples are from a number of ranges or areas and include some apparently reused timbers. All but one of the dated timbers appear to have been felled during the latter half of the fifteenth century and the first half of the sixteenth century. The exception to this is a door lintel from tower 2 which dates to the final quarter of the seventeenth century or the very early eighteenth century.

CONTRIBUTORS
Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
The Laboratory would like to thank Mr and Mrs Dickens for allowing sampling to be undertaken and for their hospitality during the process. Neil Finn kindly accompanied us on site, providing invaluable guidance and allowed us access to his building report from which figures used to locate samples are reproduced in this report. Thanks are also given to the English Heritage Scientific Dating Team who commissioned the work and also for their advice and assistance throughout the production of this report.

ARCHIVE LOCATION
Leicestershire & Rutland SMR
Historic & Natural Environment Team
Leicestershire County Council
Room 500, County Hall
Leicester Road, Glenfield
Leicestershire LE3 8TE

DATE OF INVESTIGATION
2011–12

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

# CONTENTS

# INTRODUCTION

Groby Old Hall is a Grade II* listed building located in the village of Groby, just to the north-west of Leicester (Figs 1–3). The Old Hall forms part of an extensive complex with origins in the pre-Conquest period. However, with the exception of some reused stonework and perhaps a boundary wall, there are no remains within the extant building which are thought to pre-date the fifteenth century. There have been numerous alterations and additions since the fifteenth century which have resulted in the building as seen today (Fig 4).

The manor of Groby was granted to Hugh de Grentmesnil by William I at the Norman Conquest. After several owners, it passed to the Ferrers family who held it from AD 1279 to AD 1445. The marriage of Elizabeth Ferrers and Edward Grey (later made Lord Ferrers and Baron Grey of Groby) passed the manor to the Grey family. Thomas Grey (AD 1451–1501) undertook a major building campaign at Groby but abandoned his plans to concentrate on the nearby Bradgate House, where the family seat was eventually relocated in the early sixteenth century, and after which Groby declined in importance.

## Range A (former open hall)

At the core of the extant building are the remains of a former open hall, believed to be fifteenth century in date (Figs 5 and 6). Only one bay survives, but it is thought likely that the hall originally extended to the north-west by at least one further bay. A single truss survives, at the junction between this range and the adjacent cross-wing. This truss consists of principal rafters, collar, and tiebeam and is studded above and below the collar (Fig 5). The purlins are clasped between the collar and principal rafters; the existing purlins are thought to be replacements.

Both the timbers of the truss and a number of those common rafters considered to be primary are smoke blackened indicating that the hall was originally open from the ground floor. Other common rafters show signs of previous use.

## Range G (cross-wing)

To the south-west of the hall is the cross-wing; a two-storey, plus attics, range believed to date to the late-sixteenth century (Pevsner and Williamson 1992). It is divided on all floors into two main rooms. The roof is of four bays and five trusses originally, although that at the south-east end has been removed and the gable rebuilt in brick. Each surviving truss consists of principal rafters, with collar and tiebeam (Fig 7). The timbers are well finished with chamfered edges and the principal rafters have a slight camber to their underside. There are also windbraces between the principal rafters and purlins, and a repair to one of the principal rafters of truss 1 is thought to be an original purlin (Fig 8).The centre truss (truss 2) is closed forming two separate attic rooms.

## Range E

To the south-west of the cross-wing is another two-storey, plus attic, range. Although access to this range is now via the cross-wing, the presence of a blocked doorway at first-floor level indicates that there was once access from a since demolished wing to the north-west. Differences in floor height at each level between this range and the cross-wing suggest they were built at different times, with this range thought to pre-date the cross-wing.

The roof over this range is very simple, of common-rafter type, with no collars and a single purlin to each side (Fig 9). A large number of the timbers show signs of reuse.

## Range F

In the south-east angle between the former open hall and the cross-wing is a small, square range. Its lower portion is of brick and may represent the remains of a tower; above which it is mostly stone built. Some of the masonry used in the construction of this range is obviously reused, perhaps from an earlier structure on the site. There are blocked windows in the gable end at all levels.

The roof consists of a single principal rafter truss (Fig 10). The curved principal rafters are tenoned into the tiebeam and halved at the apex to carry the ridgebeam. There are raking struts nailed into position which carry the purlins. Stylistically this roof could be either sixteenth or seventeenth century, however within the overall development sequence it is suggested it may be late-sixteenth century (Finn *et al* 2009). A number of the timbers within the roof itself show obvious signs of reuse.

## Range H (stair tower)

In the northern angle between the cross-wing and the former open hall is another small, near-square range which houses the staircase. The roof of this range is identical to that of Range F, consisting of a single truss of principal rafters tenoned into a tiebeam and halved at the apex to carry a ridgebeam (Fig 11). As with Range F it is also stylistically thought to be either sixteenth or seventeenth century, but again a sixteenth-century date seems likely (Finn *et al* 2009). This roof contains a number of timbers which appear to be reused.

### Range B (tower 1)

This tower, the furthest away from the house, is three storeys high above a brick-vaulted undercroft (Fig 12). It is possible that there is more than one building phase represented within this structure but it is generally accepted to be the work of Thomas Grey undertaken between about AD 1488 and AD 1492. There are few internal features remaining except lintels (Fig 13) and a fragment of the first-floor structure (Fig 14). The tower had been converted into a dovecote by the early nineteenth century.

### Range C (tower 2)

This second tower is narrower and shorter than tower 1 and the lower portion of it was destroyed in the twentieth century to form a garage (Fig 15). The lower of the two openings in the south-east elevation are thought to be nineteenth-century insertions (Figs 15 and 16). There is access between this tower and adjacent structure to the south-west (Fig 17). This tower is also thought to be the work of Thomas Grey, dating to the last decades of the fifteenth century.

### Range D

This was a three-storey range, aligned northeast-southwest but all that remains now is its south-east wall. This runs from tower 1 (Range B) to the cross-wing, although part of it was lost when the garage incorporating the bottom of tower 2 (Range C) was constructed. The splayed opening of the remaining first-floor window can be seen from the north-west, above which is a timber lintel (Fig 18). The lower section of the wall is stone built, with fifteenth-century brick above. It may be that the stone-built element represents an earlier boundary wall incorporated into the late fifteenth-century structure.

## SAMPLING

Sampling was requested by Tim Allen, English Heritage Inspector of Ancient Monuments, to complete a programme of investigative work as part of repairs to the building. It was hoped that successful tree-ring analysis would provide independent dating evidence for the different areas under investigation and hence clarify their relationship to each other.

A total of 65 timbers was sampled by coring. Each sample was given the code GRO-B (for Groby, site 'B') and numbered 01–65.  Fifteen of these are from the hall roof (GRO-B01–15), 12 from the cross-wing roof (GRO-B16–27), six from the range E roof (GRO-B28–33), 12 from the range F roof (GR0-B34–45), 12 from the range H roof (GRO-B46–57), three from tower 1 (GRO-B58–60), one from the lintel of the 'lost' range D (GRO-B61), and four from tower 2 (GRO-62–5). The location of samples was noted at the time of sampling and has been marked on Figures 16–22. Further details relating to the samples can be found in Table 1. The buildings lie on a northeast-southwest alignment but for the purpose of this report a site-north has been assigned with Range A at the north end and Range B at the south end.

Sampling of the staircase in Range H was not conducted because the softwood spindles are turned which would have removed all sapwood and they are of relatively small scantling which coring would have resulted in unacceptable visual impact. Other components are of fast-grown oak and hence unsuitable for analysis.

## ANALYSIS AND RESULTS

It was seen that nine of the samples (two from the former open hall, two from the cross-wing, two from range F, one from range H, one from tower 1, and one from tower 2) had too few rings to make secure dating a possibility and these samples were discarded prior to measurement. The remaining 56 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in the formation of two groups.

Firstly, 45 samples matched each other and were combined to form GROBSQ01, a site sequence of 196 rings (Fig 23). This was compared against a series of relevant reference chronologies where it was found to span the period AD 1321–1516. The evidence for this dating is given in the *t*-values in Table 2.

Three further samples grouped to form GROBSQ02, a site sequence of 71 rings (Fig 24). Attempts to date this site sequence by comparing it against the reference chronologies were unsuccessful and it remains undated.

Attempts to date the remaining ungrouped samples by comparing them individually against the reference chronologies resulted in sample GRO-B40 being found to span the period AD 1400–62 and sample GRO-B62 the period AD 1577–1668. The evidence for this dating is given by the *t*-values in Tables 3 and 4. The remaining samples are undated.

## INTERPRETATION

Tree-ring analysis of samples taken from timbers in different ranges of this building has resulted in the successful dating of 47 samples. To aid interpretation the dated samples (Fig 25) from each area have been dealt with section by section below. All felling date ranges have been calculated using the estimate that mature oak trees from this region have between 15 and 40 sapwood rings.

## Range A (former open hall)

Ten of the samples taken from this part of the building have been successfully dated; seven from the closed truss, two common rafters, and a wall plate: the latter three thought to be reused at the time of sampling. Six of these have the heartwood/sapwood boundary ring; five of which, including the wall plate and one of the two common rafters, are broadly contemporary and suggestive of a single felling. The average of these is AD 1479, allowing an estimated felling date to be calculated for the timbers represented of AD 1494–1519. The sixth sample (GRO-B13) has a slightly earlier heartwood/sapwood boundary of AD 1453, giving the timber represented, the other common rafter, a felling date range of AD 1468–93.

The other four samples without the heartwood/sapwood boundary ring (GRO-B05, GRO-B06, GRO-B07, and GRO-B08), all taken from stud posts of the truss, have last-measured heartwood ring dates which make it possible that they were felled in either of the two calculated felling date ranges. However, the level at which these four samples match each other and the rest of the dated samples from this range suggests they should belong to the AD 1494–1519 felling. Sample GRO-B05 matches samples GRO-B06 and GRO-B07 at the high values of $t$=13.6 and 10.3, respectively. This is of a level which might suggest timbers cut from the same tree; both samples GRO-B05 and GRO-B06 match GRO-B08 at levels in excess of $t$=6.0. Additionally, sample GRO-B08 matches GRO-B09, also taken from a stud post, at the value of $t$=11.2. This is again of a level which might suggest both beams were cut from the same tree and so felled at the same time. Sample GRO-B09 belongs to the later felling group, dating to AD 1494–1519.

## Range G (cross-wing)

Nine of the samples taken from the roof of this range were successfully dated. Six of these have the heartwood/sapwood boundary, which in all cases is broadly contemporary and suggestive of a single felling. The average of these is AD 1510 which allows an estimated felling date to be calculated for the timbers represented of AD 1525–50. The other three dated cross-wing samples have last-measured ring dates which make it possible that they were also felled in AD 1525–50.

## Range E

All six of the samples taken from this range were successfully dated, two of which have the heartwood/sapwood boundary ring, the dates of which suggests at least two different fellings. A common rafter has the heartwood/sapwood boundary ring date of AD 1463, giving an estimated felling date range of AD 1489–1503. This felling date range allows for sample GRO-B31 having a last-measured ring date of AD 1488 with incomplete sapwood. Another common rafter has AD 1493 for its heartwood/sapwood boundary ring date and the estimated felling date of AD 1508–33. The four samples without the heartwood/sapwood boundary ring date have last-heartwood ring dates which give *terminus post quem* dates of AD 1450 (GRO-B32), AD 1451 (GRO-B33), AD 1459 (GRO-B30), and AD 1477 (GRO-B28). All of these samples were taken from timbers which showed signs of reuse.

## Range F

During sampling of this range attempts were made to separate those beams which were thought to be primary from those which were believed to be reused (Table 1). Nine of these samples have been successfully dated, four from timbers thought to be primary and five from those with signs of reuse. Five have the heartwood/sapwood boundary ring date which suggests possibly three different fellings. Two samples, one believed primary and one reused, have similar heartwood/sapwood boundary ring dates, the average of which is AD 1456, giving an estimated felling date range for the two timbers (GRO-B38 and GRO-B41) represented of AD 1471–96. Another two (GRO-B39 and GRO-B42), again one thought primary and one reused, have the average heartwood/sapwood boundary ring date of AD 1480 and the estimated felling date range of AD 1495–1520. Finally, sample GRO-B45, from a 'reused' timber has the heartwood/sapwood boundary ring date of AD 1499 which allows an estimated felling date to be calculated of AD 1514–39. The last-measured heartwood ring dates of the other dated samples from this roof range from AD 1451 (GRO-B43) to AD 1490 (GRO-B44), all of which could fit into one or more of the estimated felling date ranges calculated or could indeed represent totally different felling/s. It can be seen that the felling dates gained do not reflect the 'primary' or 'reused' status as might have been expected.

## Range H (stair tower)

Eight of these samples were dated, three thought to be primary and five reused (Table 1); five of these dated samples have the heartwood/sapwood boundary ring date. One of these, GRO-B56, taken from a beam thought to be reused, has a slightly earlier than the rest at AD 1453, giving an estimated felling date range of AD 1468–93. The average heartwood/sapwood boundary ring date for the other four (one which was thought to be primary and three reused) is AD 1466, giving an estimated felling date range of AD 1481–1506. The other three samples (a mixture of reused and primary beams) have last-measured heartwood ring dates which make it possible that they were felled in either of the felling date ranges or represent totally different felling/s. It can be seen that in the same way as with the dates from range F, we have primary and reused timbers with the same felling date.

### Range B (tower 1)

The two floor beams were successfully dated; one to a last-measured ring date of AD 1450 and the other to a last-measured ring date of AD 1481. Neither of these samples have the heartwood/sapwood boundary ring date and so estimated felling date ranges cannot be calculated for them except that this would be estimated to be at the earliest AD 1466 and AD 1497 respectively. These make it possible that both beams were felled at the same time or alternatively they could have been felled at totally different times.

### Range C (tower 2)

One of the door lintels and one of the window lintels were successfully dated. The door lintel (GRO-B62) has the heartwood/sapwood boundary ring date of AD 1662, allowing an estimated felling date to be calculated for the timber represented of AD 1677–1702. The other sample (GRO-B65), taken from a window lintel, does not have the heartwood/sapwood boundary ring, but the last-measured heartwood ring date of AD 1478, gives the timber represented a *terminus post quem* of AD 1493.

### Range D

The exterior lintel sampled from the remains of this range has been dated to a last-measured ring date of AD 1468. Without the heartwood/sapwood boundary it is not possible to estimate a felling date for this timber, except to give it a *terminus post quem* of AD 1483.

## DISCUSSION

Prior to tree-ring analysis being undertaken at Groby Old Hall the former open hall was believed to be the oldest surviving part of the complex, thought to date to the fifteenth century. Subsequent alterations and additions were made to the building during the following centuries, with Thomas Grey credited with undertaking significant work during the period AD 1488–92.

The earliest dated timber from the former open hall is a common rafter, thought to be reused, which is now known to have been felled in AD 1468–93. However, the majority of the dated timber from this part of the building appears to have been felled in AD 1494–1519. This felling date range is represented by timbers of the truss, a common rafter, and a wall plate. These latter two timbers were believed, at the time of sampling, to have been reused, due to the presence of redundant mortices. It may be that all of these timbers are reused or, perhaps more likely, that the roof has undergone some re-organisation/repair resulting in the empty mortices.

It is unfortunate that site sequence GROBSQ02, containing three further hall samples including both principal rafters, could not be dated. This is most likely due to a series of re-occurring bands of narrow rings seen on each of these samples. These periods of restricted growth may relate to a particular woodland management regime or other non-climatic influence which has interrupted the climatic signal necessary for successful matching.

Range E was thought to predate the cross-wing on the basis of constructional details. Unfortunately, none of the apparently primary timbers of the roof were suitable for tree-ring dating but a number of the reused ones have been dated. These demonstrate that it contains timber from at least two separate fellings as indicated by two common rafters that have felling date ranges of AD 1489–1503 and AD 1508–33. For these to have been incorporated into the structure (unless they are replacements or repairs), construction must have occurred sometime after the latest felling date range.

Range F contains timber from at least three separate fellings. The earliest of these relate to a common rafter and a strut, dated to AD 1471–96. The lintel of the blocked window and a common rafter date to AD 1495–1520, whilst a reused collar has a felling date range of AD 1514–39.

The majority of the timbers from the Stairway roof have been dated to a felling of AD 1481–1506, with just one reused common rafter having the potentially earlier felling of AD 1468–93.

These two roofs are thought to be contemporary being of identical construction technique; both believed to date to the sixteenth or seventeenth century. The dated samples came from a mixture of primary and apparently reused timbers and with such a range of dates it is difficult to interpret them confidently. The majority of the timber was felled in the last decades of the fifteenth and the early decades of the sixteenth century, although a number of these timbers were thought to be reused at the time of sampling. The inclusion of a reused collar of AD 1514–39, demonstrates work being undertaken after this time, although it is possible that this timber is a later replacement, added to strengthen the roof. It is unfortunate, that the timbers which could have been more confidently identified as primary, the tiebeams and principal rafters were either unsuitable or are undated.

The two first-floor frame beams which survive in tower 1 have been dated to after AD 1465 and after AD 1496, although unfortunately, it is not possible to say how long after. This suggests construction of the floor at least, and possibly the tower itself also took place sometime after AD 1496.

One of the window lintels in tower 2 has been dated to after AD 1493, although again it is not possible to say how long after. One of the door lintels, over the access from the adjacent building to this tower is now known to have been felled in AD 1677–1702.

It had been suggested that these towers were erected by Thomas Grey during the period of his great rebuilding. The dates gained would suggest that if Thomas Grey was the architect of this work then he continued with his modifications and plans for slightly longer than previously thought.

The lintel seen in the exterior wall of the remains of the 'lost' range D is now known to have been felled after AD 1483.

The cross-wing roof had been dated stylistically to the sixteenth century. This has now been further refined by the dendrochronological dating of several of the timbers used in its construction to AD 1525–50. It had been suggested (Finn *pers comm*) that an original purlin had been used to repair one of the principal rafters of truss 1. This has now been confirmed with the timber under discussion (GRO-B16) dating to the second quarter of the sixteenth century with the rest of the dated timber from this range. Furthermore, this sample matches against one taken from another purlin (GRO-B23) at the high value of $t$=16.9 making it likely that these two timbers were cut from the same tree.

The potential same tree matches seen amongst the samples taken from the studs of the former open hall truss have been mentioned above. Additionally, high $t$-value matches have been noted between samples from different areas; sample GRO-B43, taken from a 'reused' timber within the roof of Range F matches GRO-B13 from the former open hall at a value of $t$=13.5.

It may be significant that the majority of the felling date ranges outlined above do encompass the period AD 1488–92, supporting the suggestion that this was a period of much activity at Groby Old Hall although how many of these timbers are still in their primary positions is unclear.

## BIBLIOGRAPHY

Alcock, N W, Howard, R E, Laxton, R R, and Litton, C D, and Miles, D H, 1990 Leverhulme Cruck Project Results 1989, *Vernacular Architect*, **21**, 42–4

Howard, R E, Litton, C D, and Arnold, A J, 2005 *Tree-Ring Analysis of Timbers from the Main Guard, Pontefract Castle, Pontefract, West Yorkshire*, Centre for Archaeol Rep, **48/2005**

Arnold, A J, Howard, R E, and Tyers, C, 2008a *Ulverscroft Priory, Ulverscroft, Charnwood Forest, Leicestershire, Tree-ring analysis of timbers*, Res Dept Rep Ser, **48/2008**

Arnold, A J, Howard, R E, and Litton, C D, 2008b Nottingham Tree-Ring Dating Laboratory: additional dendrochronology dates, *Vernacular Architect*, **39**, 107–11

Arnold, A J, Howard, R E, and Litton, C D, 2008c Nottingham Tree-Ring Dating Laboratory, *Vernacular Architect*, **39**, 119–28

Arnold, A J, and Howard, R E, 2009a *Tree-ring analysis of timbers from 1–3 Northgate, Newark, Nottinghamshire*, NTRDL rep

Arnold, A J, and Howard, R E, 2009b unpubl composite working mean of samples from Westernhanger Barn, and the Dovecote, Westernhanger Castle, Folkestone, Kent, unpubl computer file *WHBCSQ01*, NTRDL

Arnold, A J, and Howard, R E, 2009c unpubl Tree-ring analysis of timbers from Castle House, Castle Street, Melbourne, Derbyshire, unpubl computer files *MLBCSQ01/2*, NTRDL

Arnold, A J, and Howard, R E, 2009d unpubl Tree-ring analysis of timbers from Walnut Cottage, Boat Lane, Hoveringham, Nottinghamshire, unpubl computer file *HOVASQ01*, NTRDL

Arnold, A J, and Howard, R E, 2012 *Tree-ring analysis of timbers from The Old Rectory, Wiveton Road, Blakeney, Norfolk*, NTRDL rep

Finn, N, Coward, J, and Clarke, S, 2009 *Groby Old Hall, Markfield Road, Groby, Leicestershire: Historic Building Assessment: NGR SK 5239 0759*, ULAS Rep **2009–126**

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1986 Nottingham University Tree-ring Dating Laboratory: results, *Vernacular Architect*, **17**, 52–3

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1991 Nottingham University Tree-Ring Dating Laboratory: results, *Vernacular Architect*, **22**, 40–3

Howard, R E, Laxton, R R, Litton, C D, Morrison, A, Sewell, J, and Hook, R, 1997 Nottingham University Tree-Ring Dating Laboratory: Derbyshire, Peak Park and RCHME dendrochronological survey 1996–7, *Vernacular Architect*, **28**, 128–9

Howard, R E, Laxton, R R, and Litton, C D, 2000 *Tree-ring analysis of timbers from Stoneleigh Abbey, Stoneleigh, Warwickshire*, Anc Mon Lab Rep, **80/2000**

Laxton, R R, Litton, C D, and Simpson, W G, 1984 Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in Eastern and Midland England, *Vernacular Architect*, **15**, 65–8

Pevsner, N, and Williamson, E, 1992 *The Buildings of England: Leicestershire and Rutland* London: Penguin Books

Tyers, I, 2001 *Dendrochronological analysis of timbers from New House Grange Tithe Barn, Sheepy Magna, Leicestershire*, ARCUS Rep, **574d**

Tyers, I, 2004 *Medieval Pembridge: Report on the tree-ring analysis of properties in the village*, ARCUS Rep, **778**

# TABLES

*Table 1: Details of tree-ring samples from Groby Hall, Groby, Leicestershire*

| Sample number | Sample location | Total rings* | Sapwood rings** | First measured ring date (AD) | Last heartwood ring date (AD) | Last measured ring date (AD) |
|---|---|---|---|---|---|---|
| Range A (former open hall) | | | | | | |
| GRO-B01 | Tiebeam | 86 | h/s | 1397 | 1482 | 1482 |
| GRO-B02 | East principal rafter | 56 | h/s | ---- | ---- | ---- |
| GRO-B03 | West principal rafter | 67 | h/s | ---- | ---- | ---- |
| GRO-B04 | Collar | 62 | h/s | 1418 | 1479 | 1479 |
| GRO-B05 | Stud (middle above collar) | 74 | -- | 1360 | ---- | 1433 |
| GRO-B06 | Stud | 93 | -- | 1349 | ---- | 1441 |
| GRO-B07 | Stud | 92 | -- | 1352 | ---- | 1443 |
| GRO-B08 | Stud 8 (from east) | 94 | -- | 1362 | ---- | 1455 |
| GRO-B09 | Stud 1 (from east) | 115 | h/s | 1357 | 1471 | 1471 |
| GRO-B10 | West common rafter 4 (smoke blackened) | NM | -- | ---- | ---- | ---- |
| GRO-B11 | West common rafter 5 (smoke blackened) | NM | -- | ---- | ---- | ---- |
| GRO-B12 | East common rafter 8 (smoke blackened) | 64 | h/s | ---- | ---- | ---- |
| GRO-B13 | East common rafter 11 (reused) | 99 | 07 | 1362 | 1453 | 1460 |
| GRO-B14 | East common rafter 12 (reused) | 107 | h/s | 1376 | 1482 | 1482 |
| GRO-B15 | East wallplate (reused) | 86 | h/s | 1394 | 1479 | 1479 |
| Range G (cross-wing) | | | | | | |
| GRO-B16 | North principal rafter, truss 1 (repair) | 101 | h/s | 1408 | 1508 | 1508 |
| GRO-B17 | North principal rafter, truss 1 | 61 | h/s | 1451 | 1511 | 1511 |
| GRO-B18 | South principal rafter, truss 1 | 110 | h/s | 1399 | 1508 | 1508 |
| GRO-B19 | North principal rafter, truss 2 | 57 | -- | ---- | ---- | ---- |
| GRO-B20 | South principal rafter, truss 2 | NM | -- | ---- | ---- | ---- |
| GRO-B21 | South principal rafter, truss 3 | 105 | h/s | 1407 | 1511 | 1511 |
| GRO-B22 | North purlin, truss 1–2 | 144 | -- | 1321 | ---- | 1464 |
| GRO-B23 | North purlin, truss 2–3 | 100 | -- | 1395 | ---- | 1494 |
| GRO-B24 | South purlin, east gable truss 1 | 139 | h/s | 1378 | 1516 | 1516 |

| | | | | | | |
|---|---|---|---|---|---|---|
| GRO-B25 | South purlin, truss 1–2 | NM | -- | ---- | ---- | ---- |
| GRO-B26 | South purlin, truss 2–3 | 88 | -- | 1349 | ---- | 1436 |
| GRO-B27 | South purlin, truss 3–4 | 140 | h/s | 1366 | 1505 | 1505 |
| Range E (reused) | | | | | | |
| GRO-B28 | East common rafter 3 | 94 | -- | 1369 | ---- | 1462 |
| GRO-B29 | East common rafter 5 | 58 | h/s | 1436 | 1493 | 1493 |
| GRO-B30 | East common rafter 6 | 75 | -- | 1370 | ---- | 1444 |
| GRO-B31 | West common rafter 2 | 83 | 25 | 1406 | 1463 | 1488 |
| GRO-B32 | East wallplate | 92 | -- | 1344 | ---- | 1435 |
| GRO-B33 | West wallplate | 63 | -- | 1374 | ---- | 1436 |
| Range F (primary) | | | | | | |
| GRO-B34 | Tiebeam | NM | -- | ---- | ---- | ---- |
| GRO-B35 | North principal rafter | NM | -- | ---- | ---- | ---- |
| GRO-B36 | South principal rafter | 47 | 10 | ---- | ---- | ---- |
| GRO-B37 | North strut | 69 | -- | 1419 | ---- | 1487 |
| GRO-B38 | South strut | 71 | 01 | 1388 | 1457 | 1458 |
| GRO-B39 | Lintel | 126 | h/s | 1353 | 1478 | 1478 |
| GRO-B40 | Collar, frame 1 | 63 | -- | 1400 | ---- | 1462 |
| Range F (reused) | | | | | | |
| GRO-B41 | South common rafter 6 | 74 | 02 | 1383 | 1454 | 1456 |
| GRO-B42 | South common rafter 7 | 103 | h/s | 1379 | 1481 | 1481 |
| GRO-B43 | South common rafter 9 | 99 | -- | 1353 | ---- | 1451 |
| GRO-B44 | South common rafter 11 | 57 | -- | 1434 | ---- | 1490 |
| GRO-B45 | Collar, frame 4 | 167 | h/s | 1333 | 1499 | 1499 |
| Range H (stair tower) (primary) | | | | | | |
| GRO-B46 | Tiebeam | 56 | 15+6 | ---- | ---- | ---- |
| GRO-B47 | North principal rafter | NM | -- | ---- | ---- | ---- |
| GRO-B48 | South principal rafter | 48 | 09+3 | ---- | ---- | ---- |
| GRO-B49 | North common rafter 2 | 84 | -- | 1323 | ---- | 1406 |
| GRO-B50 | North common rafter 8 | 92 | h/s | 1379 | 1470 | 1470 |
| GRO-B51 | South common rafter 5 | 124 | -- | 1338 | ---- | 1461 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Range H (stair tower) (reused) | | | | | | |
| GRO-B52 | North common rafter 5 | 75 | -- | ---- | ---- | ---- |
| GRO-B53 | North common rafter 7 | 85 | h/s | 1381 | 1465 | 1465 |
| GRO-B54 | South common rafter 3 | 62 | h/s | 1404 | 1465 | 1465 |
| GRO-B55 | South common rafter 7 | 103 | h/s | 1362 | 1464 | 1464 |
| GRO-B56 | South common rafter 9 | 81 | h/s | 1373 | 1453 | 1453 |
| GRO-B57 | South common rafter 10 | 65 | -- | 1357 | ---- | 1421 |
| Range B (tower 1) | | | | | | |
| GRO-B58 | North beam, first floor | 102 | -- | 1380 | ---- | 1481 |
| GRO-B59 | South beam, first floor | 93 | -- | 1358 | ---- | 1450 |
| GRO-B60 | Door lintel | NM | -- | ---- | ---- | ---- |
| Range D | | | | | | |
| GRO-B61 | External lintel | 140 | -- | 1329 | ---- | 1468 |
| Range C (tower 2) | | | | | | |
| GRO-B62 | South lintel | 92 | 06 | 1577 | 1662 | 1668 |
| GRO-B63 | Mid south lintel | NM | -- | ---- | ---- | ---- |
| GRO-B64 | First floor window lintel | 84 | -- | ---- | ---- | ---- |
| GRO-B65 | Second floor window lintel | 91 | -- | 1388 | ---- | 1478 |

*Table 2: Results of the cross-matching of site sequence GROBSQ01 and relevant reference chronologies when the first-ring date is AD 1321 and the last-ring date is AD 1436*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| Thatched Cottage, Melbourne, Derbyshire | 10.4 | AD 1372–1530 | Howard *et al* 1997 |
| Stoneleigh Abbey, Stoneleigh, Warwickshire | 10.4 | AD 1398–1658 | Howard *et al* 2000 |
| Gotham Manor, Nottinghamshire | 9.5 | AD 1391–1590 | Howard *et al* 1991 |
| April Cottage, Rothley, Leicestershire | 9.1 | AD 1343–1443 | Alcock *et al* 1990 |
| Hagworthingham Church, Lincolnshire | 9.0 | AD 1336–1533 | Laxton *et al* 1984 |
| Aisled barn, Newark, Nottinghamshire | 8.7 | AD 1249–1399 | Laxton *et al* 1984 |
| Ulverscroft Priory, Charnwood Forest, Leicestershire | 8.3 | AD 1219–1463 | Arnold *et al* 2008a |

*Table 3: Results of the cross-matching of sample GRO-B40 and relevant reference chronologies when the first-ring date is AD 1400 and the last-ring date is AD 1462*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| 1–3 Northgate, Newark, Nottinghamshire | 5.7 | AD 1339–1523 | Arnold and Howard 2009a |
| The Old Rectory, Blakeney, Norfolk | 5.6 | AD 1339–1518 | Arnold and Howard 2012 |
| Pembridge bell tower, Herefordshire | 5.4 | AD 1382–1471 | Tyers 2004 |
| Governor's House, Newark, Nottinghamshire | 5.3 | AD 1356–1448 | Howard *et al* 1986 |
| Chalgrove Manor, Chalgrove, Oxfordshire | 5.2 | AD 1355–1503 | Arnold *et al* 2008b |
| Westernhanger Barn/Castle, Dover, Kent | 5.0 | AD 1346–1581 | Arnold and Howard 2009b unpubl |
| New House Grange Barn, Sheepy Magna, Leicestershire | 5.0 | AD 1373–1506 | Tyers 2001 |

*Table 4: Results of the cross-matching of sample GRO-B62 and relevant reference chronologies when the first-ring date is AD 1577 and the last-ring date is AD 1668*

| Reference chronology | t-value | Span of chronology | Reference |
|---|---|---|---|
| Wheatsheaf, Cropwell Bishop, Nottinghamshire | 6.6 | AD 1604–1703 | Arnold *et al* 2008b |
| Pontefract Castle, Pontefract | 6.3 | AD 1507–1656 | Arnold *et al* 2005 |
| 13 Hallgate, Diseworth, Leicestershire | 6.1 | AD 1538–1671 | Arnold *et al* 2008c |
| Castle House, Melbourne, Derbyshire | 5.9 | AD 1583–1720 | Arnold and Howard 2009c unpubl |
| Oak House Barn, West Bromwich, West Midlands | 5.6 | AD 1562–1655 | Howard *et al* 1991 |
| Rufford Mill, Nottinghamshire | 5.6 | AD 1571–1727 | Laxton *et al* 1984 |
| Walnut Cottage, Hoveringham, Nottinghamshire | 5.6 | AD 1603–1676 | Arnold and Howard 2009d unpubl |

## FIGURES


*Figure 1: Map to show the general location of Groby, Leicestershire, circled. © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900*

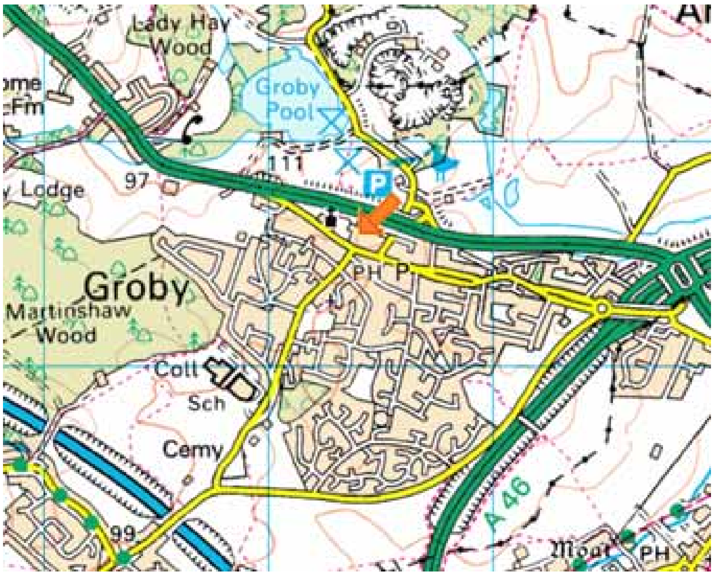



*Figure 2: Map to show the general location of Groby Old Hall, Groby, Leicestershire, arrowed. © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900*

*Figure 3: Map to show the location of Groby Old Hall, Groby, Leicestershire.  © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900*

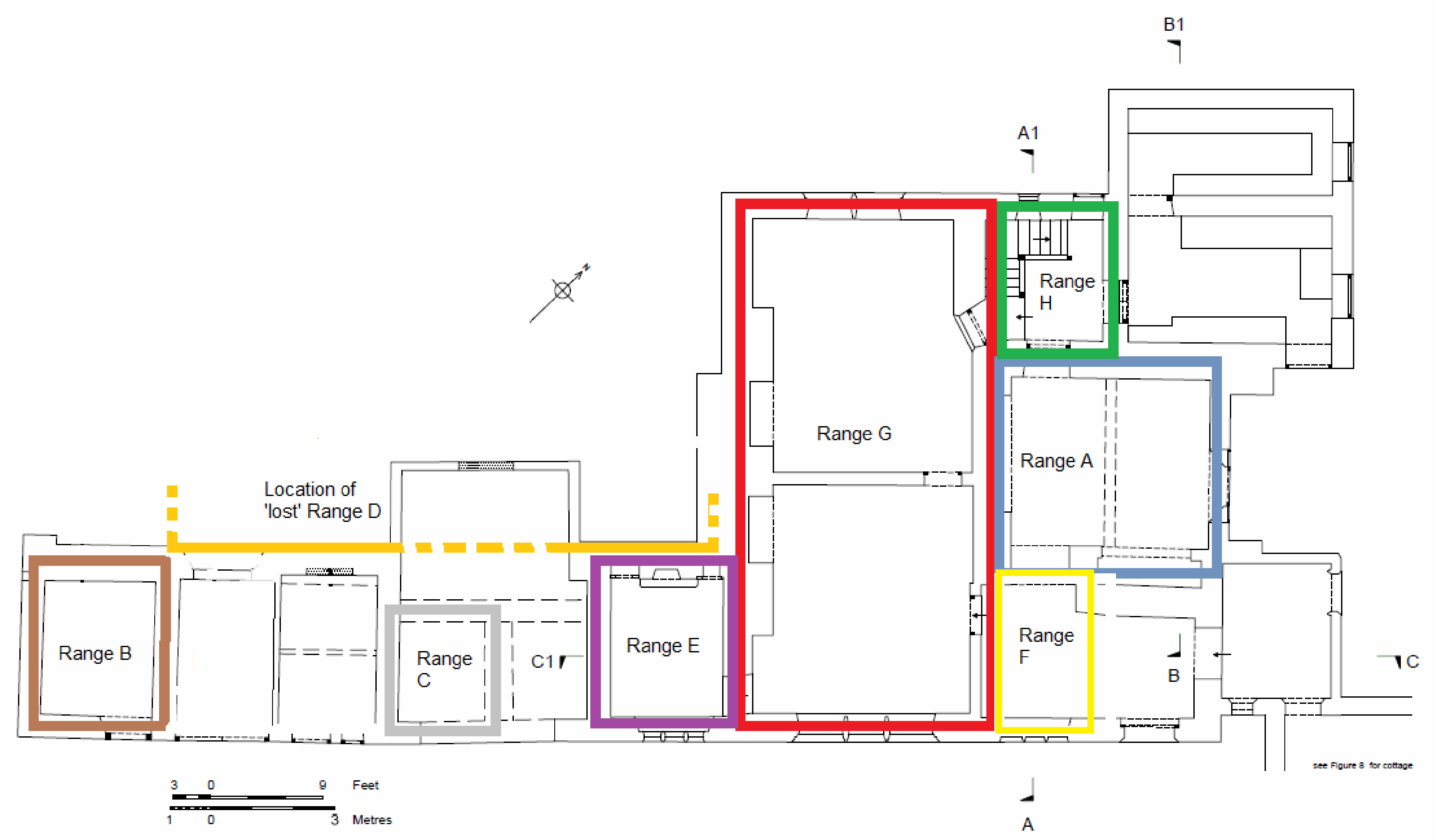



*Figure 4: Ground-floor plan showing the various areas under investigation (after Finn* et al *2009)*

*Figure 5: Smoke-blackened truss in the former open hall, photograph taken from the north (Robert Howard)*

*Figure 6: Roof of the former open hall, looking north-east (Robert Howard)*

*Figure 7: Roof truss 1 in the cross-wing, photograph taken from the north-west (Alison Arnold)*

*Figure 8: Repair to the principal rafter, truss 1 in the cross-wing, photograph taken from the south (Alison Arnold)*

*Figure 9: Roof of range E, photograph taken from the north-east (Robert Howard)*

*Figure 10: Roof of range F, photograph taken from the south-west (Robert Howard)*

*Figure 11: Roof of the stair tower, photograph taken from the south-east (Alison Arnold)*

*Figure 12: Tower 1, photograph taken from the south (Robert Howard)*

*Figure 13: Tower 1 door lintel, photograph taken from the north-west (Alison Arnold)*

*Figure 14: Remnants of the first-floor frame in tower 1, photograph taken from below (Alison Arnold)*

*Figure 15: Tower 2, south-east elevation with openings, photograph taken from the east (Alison Arnold)*


*Figure 16: Tower 2 window lintels (GRO-B64 and GRO-B65), photographs taken from the north-west (Alison Arnold)*

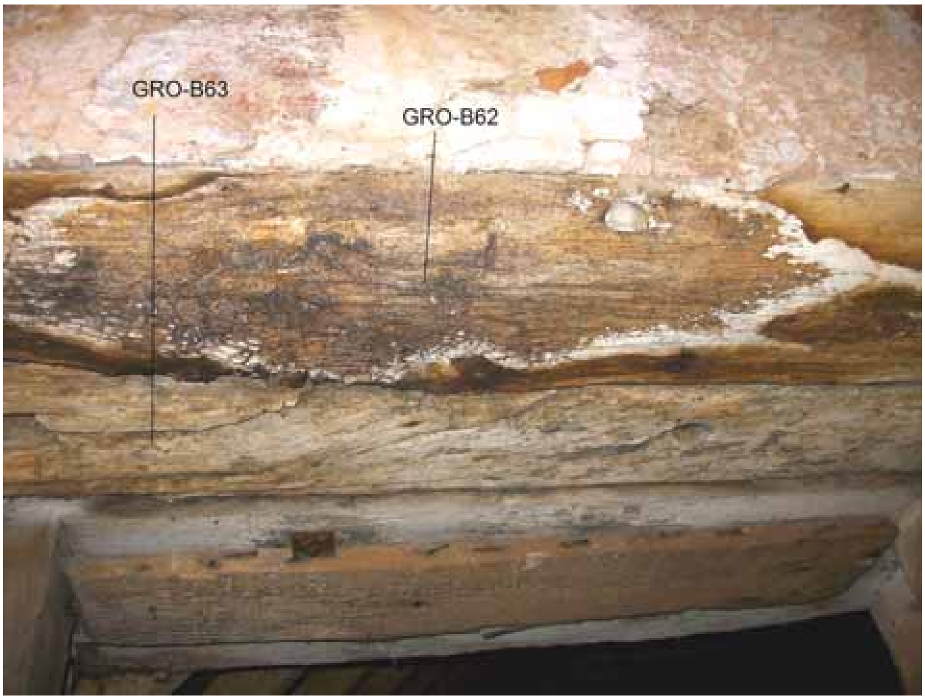



*Figure 17: Tower 2 door lintels (GRO-B62 and GRO-B63), photograph taken from the south-west (Alison Arnold)*


*Figure 18: Remains of 'lost' range D with timber lintel (GRO-B61), photograph taken from the north-west (Alison Arnold)*

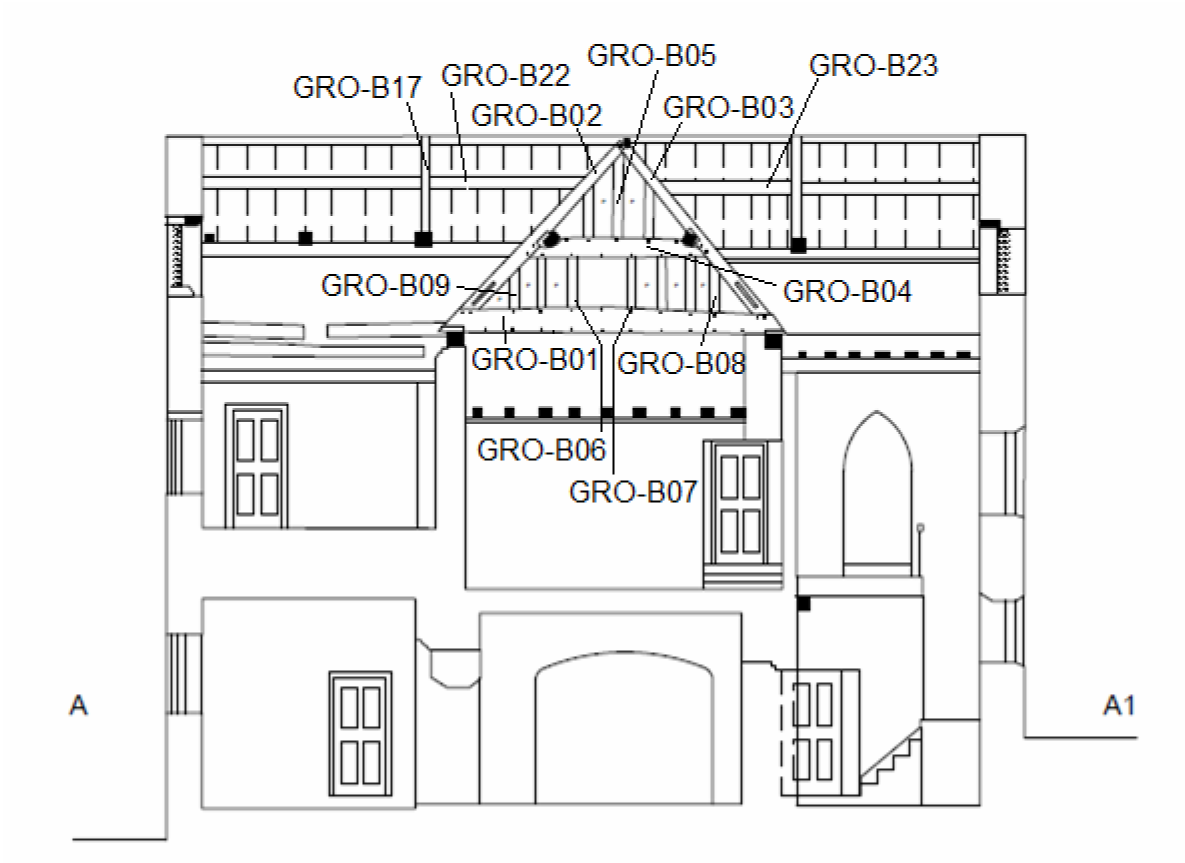



*Figure 19: Section A–A, showing the location of samples GRO-B01–09, GRO-B17, and GRO-B22–3 (after Finn* et al *2009)*

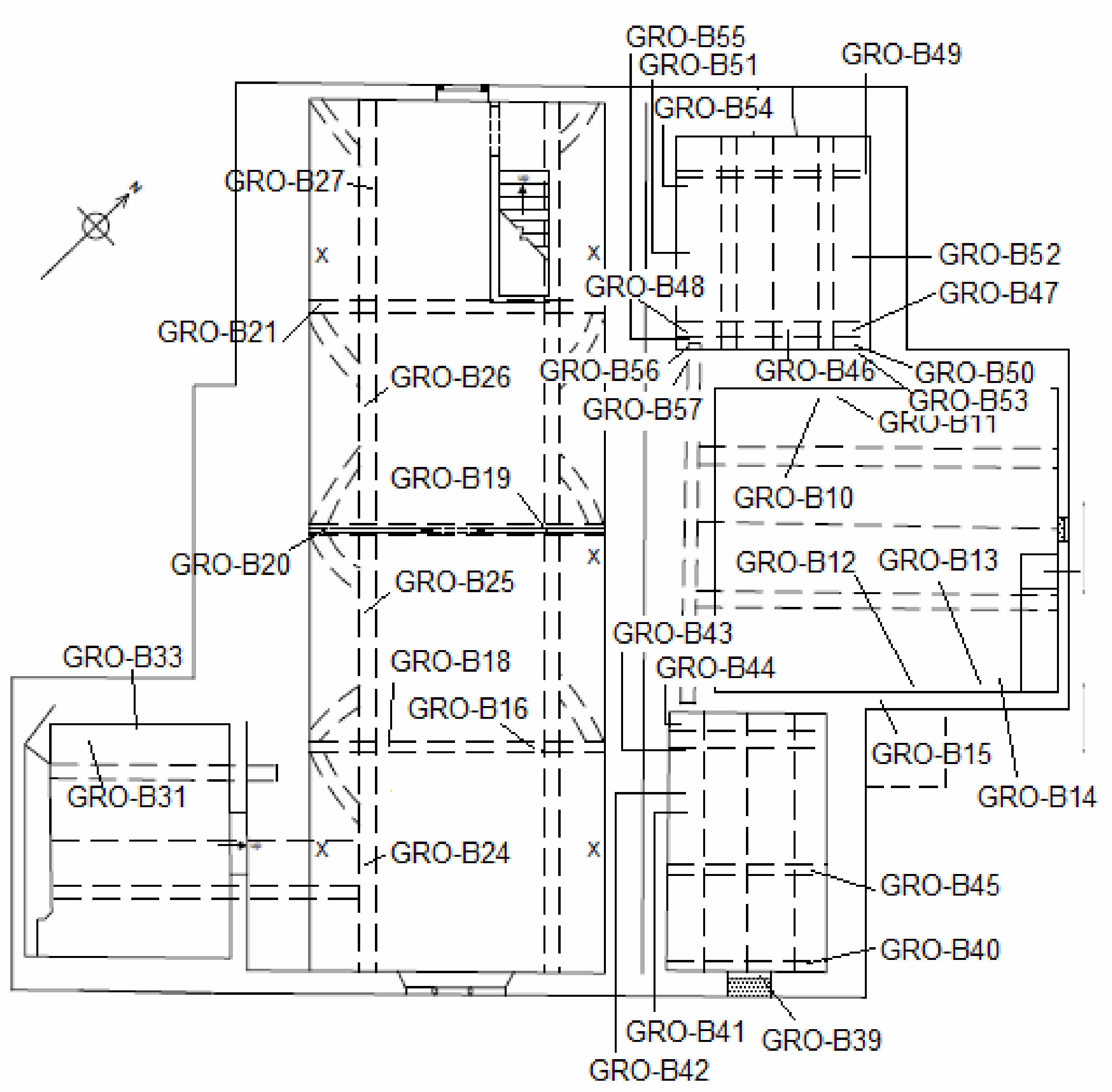



*Figure 20: Attic plan, showing the location of samples GRO-B10–16, GRO-B18–21, GRO-B24–7, GRO-B31, GRO-B33, and GRO-B39–57 (after Finn* et al *2009)*

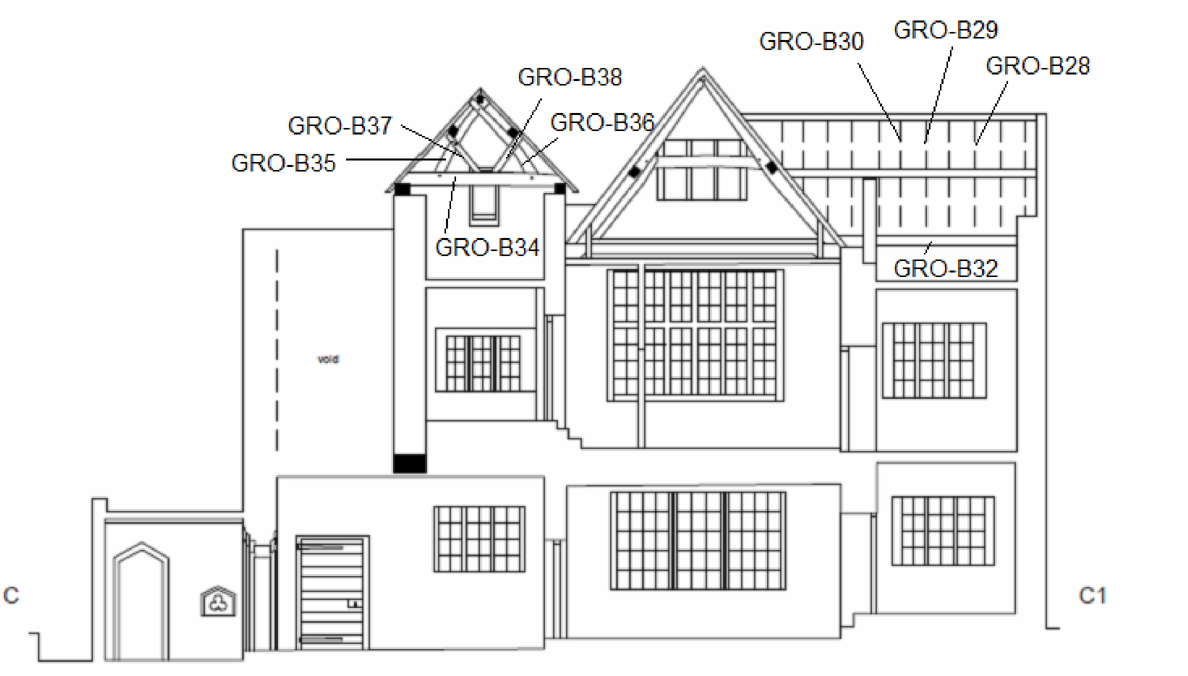



*Figure 21: Section C–C, showing the location of samples GRO-B28–30, GRO-B32, and GRO-B34–8 (after Finn* et al *2009)*

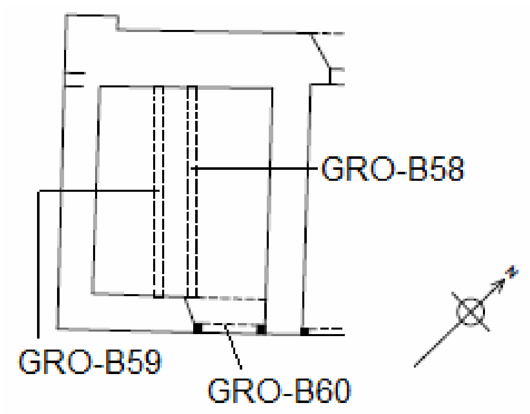



*Figure 22: Ground-floor plan of tower 1, showing the location of samples GRO-B58–60 (after Finn* et al *2009)*

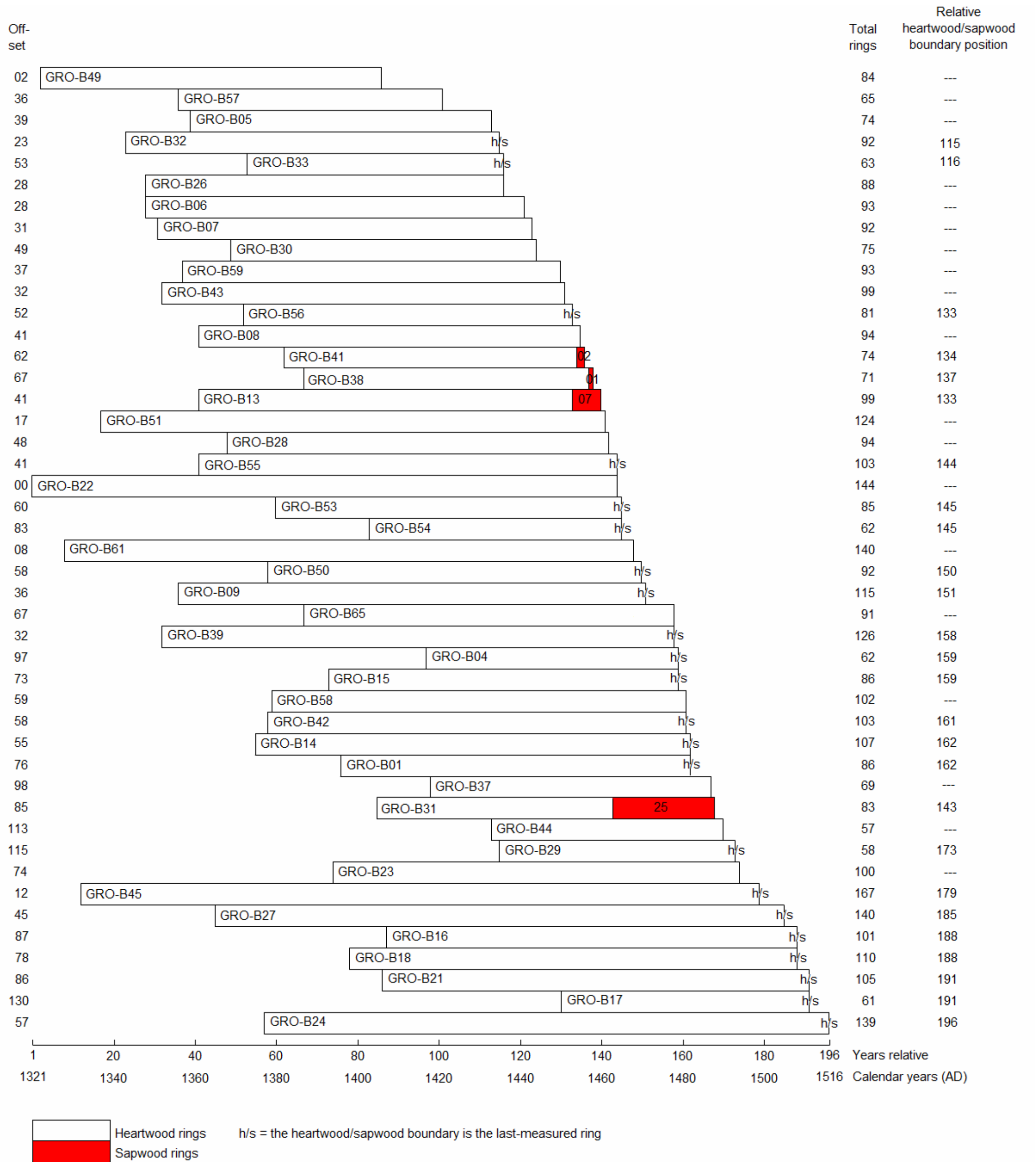



*Figure 23: Bar diagram of samples in site sequence GROBSQ01*

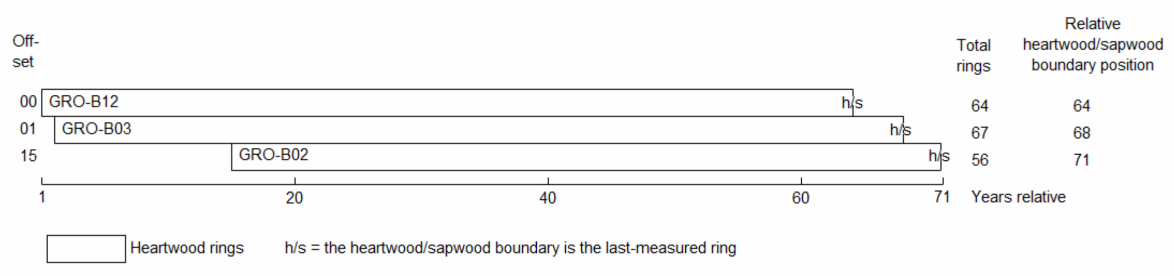



*Figure 24: Bar diagram of samples in site sequence GROBSQ02*

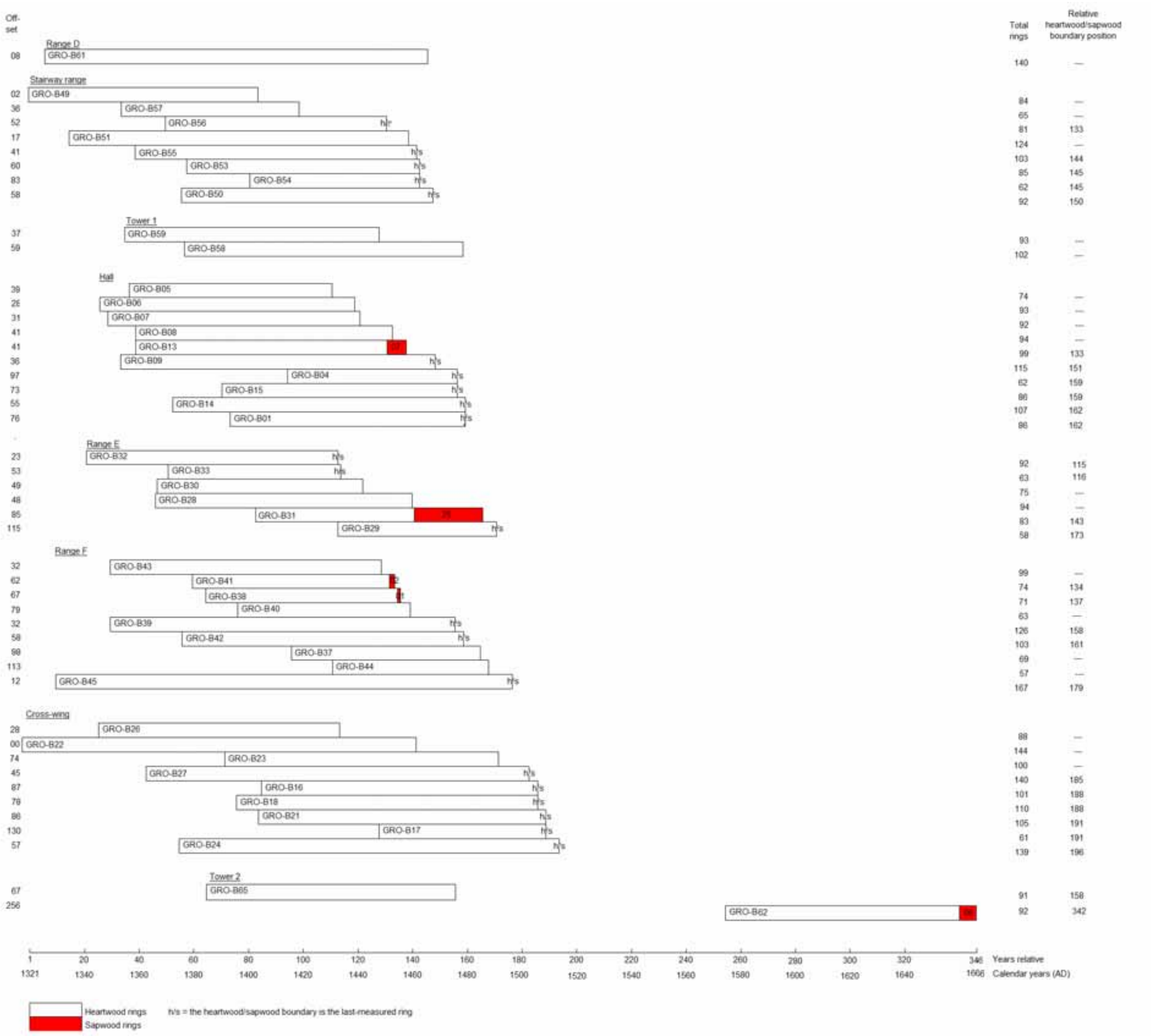



*Figure 25: Bar diagram of dated samples, sorted by area*

# DATA OF MEASURED SAMPLES

## Measurements in 0.01mm units

GRO-B01A 86
203 227 169 150 148 204 218 255 165 203 163 152 164 122 101 130 113 111 86 65
35 64 48 53 62 44 71 60 37 43 46 64 53 48 73 124 70 109 115 185
91 100 153 165 292 170 186 146 114 157 225 146 183 184 181 145 204 202 234 206
184 168 105 172 165 171 222 185 172 221 195 240 269 235 227 200 235 191 287 228
186 165 193 221 203 168
GRO-B01B 86
207 234 167 149 142 201 228 245 166 206 159 150 167 118 94 136 119 113 95 71
43 60 43 59 60 48 72 58 37 39 53 60 54 54 67 124 65 114 105 182
96 102 145 177 302 172 180 154 103 165 228 149 198 194 196 146 201 197 232 215
184 169 111 165 174 171 209 183 169 224 201 241 258 235 229 201 234 200 285 230
191 167 194 216 200 223
GRO-B02A 56
288 369 358 300 472 433 364 448 348 388 295 208 172 119 163 125 174 276 344 208
110 105 161 149 250 286 298 259 383 327 281 373 142 144 107 240 358 308 403 377
299 403 409 228 78 86 118 169 169 175 204 170 327 301 216 308
GRO-B02B 56
289 360 351 297 431 448 360 444 340 384 303 201 128 106 162 135 180 274 336 213
108 103 124 156 249 284 299 263 378 323 282 371 163 152 103 297 390 322 405 385
309 411 399 234 77 84 116 138 171 177 201 168 316 255 234 321
GRO-B03A 67
220 322 382 304 320 307 388 108 132 171 126 159 163 226 264 308 299 298 407 348
290 365 278 295 250 162 125 89 121 137 174 313 340 192 93 151 182 176 200 202
154 146 166 230 192 151 74 92 66 177 301 271 405 392 256 324 282 159 75 137
210 210 232 251 186 168 224
GRO-B03B 67
247 324 376 304 319 304 406 107 137 181 109 169 154 216 255 315 311 281 413 348
285 380 277 297 243 157 120 86 121 136 171 308 345 190 92 155 181 172 200 207
149 145 170 229 193 160 73 104 77 186 325 274 407 390 248 330 280 159 82 135
211 209 228 247 195 165 225
GRO-B04A 62
390 306 341 300 273 273 342 80 88 197 231 323 153 313 150 154 182 132 133 85
112 94 176 195 190 226 177 125 100 174 178 162 175 189 191 180 206 177 226 215
187 146 215 188 120 179 166 205 246 161 148 160 234 230 147 187 204 290 285 188
127 163
GRO-B04B 62
393 307 337 298 273 274 340 81 106 193 229 321 149 283 172 156 181 122 132 79
114 103 174 194 170 229 172 116 97 171 179 181 176 191 166 196 186 186 234 211
165 156 202 191 122 182 165 210 248 165 142 158 238 224 150 183 199 295 281 185
126 160
GRO-B05A 74
291 331 403 341 362 301 281 180 161 288 287 209 228 179 197 181 223 234 290 255
234 215 209 222 210 208 267 317 298 219 125 104 112 83 107 96 145 149 204 207
214 164 167 197 211 210 207 169 153 108 75 67 100 113 100 103 95 141 140 119
121 173 115 150 145 96 77 122 152 144 124 146 166 123
GRO-B05B 74
288 320 403 346 387 292 279 194 171 278 291 208 228 177 199 179 218 235 291 254
239 214 206 223 208 212 272 317 301 211 134 111 117 80 104 101 146 147 203 210

210 162 167 196 213 207 211 169 156 107 73 72 96 113 102 97 96 141 142 121
123 167 121 150 140 94 67 112 155 149 118 145 166 127
GRO-B06A 93
350 235 201 196 307 256 362 305 360 271 257 221 245 342 301 306 263 242 174 152
191 186 143 161 117 144 134 167 173 251 238 208 190 184 200 157 188 242 250 231
157 109 86 81 78 74 68 99 111 155 149 167 113 118 143 140 145 155 148 126
94 75 49 65 91 103 87 126 136 152 110 131 176 134 159 197 118 68 114 170
210 136 194 197 138 141 122 156 97 116 86 197 154
GRO-B06B 93
351 234 200 172 293 261 356 306 342 272 268 228 250 336 301 298 259 211 154 145
190 189 145 172 131 144 135 164 183 242 237 199 185 188 196 156 191 243 250 230
155 111 86 83 76 71 69 98 110 154 149 170 108 113 146 143 146 148 149 123
89 66 55 70 80 86 96 120 142 156 101 126 179 136 161 194 112 65 113 162
192 140 198 201 128 143 115 155 97 110 92 188 157
GRO-B07A 92
118 181 125 200 339 346 323 244 198 264 403 282 287 249 181 113 79 104 95 94
127 62 94 68 93 113 148 148 139 112 109 144 147 161 214 221 195 148 132 90
76 73 74 67 115 117 162 143 172 142 164 150 200 202 164 148 105 83 59 50
95 121 92 91 114 170 147 140 133 174 162 208 203 131 93 175 223 228 164 199
178 130 114 136 177 115 130 389 355 290 251 285
GRO-B07B 92
122 186 125 219 374 351 326 245 191 271 398 282 284 257 185 116 75 103 97 93
124 69 80 69 80 114 151 155 121 109 98 147 143 167 228 215 188 152 125 96
71 74 79 68 112 98 148 154 182 140 157 158 196 200 160 148 107 81 56 54
93 126 92 85 122 161 153 137 134 171 160 207 211 133 95 186 220 229 155 189
173 142 123 131 180 126 127 375 345 275 223 286
GRO-B08A 94
356 297 318 329 243 252 245 266 144 87 124 128 116 162 180 211 266 240 298 222
241 349 241 248 276 269 241 109 89 59 65 85 73 86 161 166 244 238 138 143
133 142 164 179 188 154 123 94 77 70 83 92 68 71 50 72 100 83 111 141
143 218 148 69 64 107 158 184 128 173 175 118 102 88 62 69 54 72 126 163
139 177 146 92 101 226 269 287 236 218 288 182 164 166
GRO-B08B 94
465 321 311 323 237 246 241 265 147 85 128 131 119 163 181 214 266 234 313 216
240 355 258 276 283 273 233 112 74 65 68 82 72 81 157 175 257 232 155 131
113 150 165 182 197 151 130 89 78 66 80 78 74 72 54 75 99 94 115 156
149 202 141 67 58 100 162 183 127 172 186 116 99 95 63 64 60 67 120 161
147 167 153 90 104 221 266 259 235 203 298 187 166 181
GRO-B09A 115
152 218 145 196 212 308 175 170 207 178 170 249 257 136 110 149 118 139 123 158
179 193 157 182 174 155 188 189 159 218 184 191 122 104 75 54 74 51 56 91
90 102 106 87 68 53 97 163 155 171 128 121 72 81 96 102 91 66 75 59
83 103 84 86 94 87 136 90 63 48 73 93 87 76 102 95 81 80 60 46
43 42 45 62 79 81 82 79 59 53 86 108 123 122 125 142 90 137 96 89
85 94 69 80 79 85 70 71 86 93 80 94 50 65 83
GRO-B09B 115
135 218 152 197 226 296 165 170 204 172 175 237 256 145 101 151 117 111 107 164
184 198 159 189 167 156 190 190 157 225 187 186 128 99 82 54 69 55 57 92
81 106 106 87 68 55 91 172 148 189 116 114 82 81 103 101 93 63 71 64
67 110 82 84 100 81 137 90 64 50 69 92 89 82 102 110 75 79 61 55
50 47 40 76 81 88 85 83 52 54 73 102 125 115 131 153 94 130 107 98
82 103 70 84 80 84 67 70 87 103 86 95 49 78 88
GRO-B12A 64

245 246 310 433 331 336 334 474 58 46 79 45 78 122 209 219 183 226 134 209
174 168 216 233 185 173 151 174 117 142 135 268 340 447 173 84 56 131 116 140
180 99 108 164 170 170 155 107 270 161 279 361 284 255 213 86 208 208 141 88
128 166 130 127
GRO-B12B 64
260 243 314 432 331 356 302 477 95 46 80 51 86 137 197 218 182 230 140 202
182 167 211 212 160 179 152 165 114 132 136 263 332 426 190 90 63 109 117 139
185 119 78 167 176 171 154 103 276 162 281 360 284 256 210 83 220 203 137 95
122 161 125 130
GRO-B13A 99
376 332 238 179 161 92 141 183 142 126 129 135 108 82 90 156 165 130 134 117
121 110 88 113 111 120 102 84 53 39 62 48 58 60 75 75 88 74 86 79
55 68 72 59 75 47 62 83 59 38 50 52 41 42 54 27 56 38 43 50
59 117 97 62 67 116 105 137 107 100 186 78 50 68 70 60 46 65 97 98
87 105 138 75 75 72 92 92 103 141 110 94 120 109 119 88 70 83 118
GRO-B13B 99
378 331 248 189 159 106 145 168 145 125 124 132 119 71 93 143 167 134 128 129
119 88 99 100 124 115 104 88 56 43 59 53 52 55 80 65 90 76 88 74
52 71 69 59 71 44 66 80 61 42 49 47 43 47 49 28 56 48 36 48
64 112 113 60 71 114 114 130 103 98 188 74 51 72 57 66 49 61 97 99
86 103 137 82 74 73 98 98 89 154 98 109 107 105 130 92 72 85 105
GRO-B14A 107
91 81 97 91 102 70 48 66 82 86 91 87 80 77 47 28 39 35 37 35
61 52 59 52 73 60 46 67 47 62 50 50 45 56 69 75 63 54 36 63
53 76 93 56 53 70 49 88 106 93 86 149 135 98 74 91 105 126 119 135
148 172 137 138 163 198 119 111 166 101 70 188 98 104 103 111 108 109 128 108
131 98 80 88 90 129 121 150 123 137 186 172 232 211 216 130 116 121 102 186
159 126 164 112 118 168 119
GRO-B14B 107
91 87 93 92 105 78 61 55 67 95 94 82 89 58 49 31 42 25 41 36
63 53 59 52 70 61 54 58 51 63 43 40 50 62 64 77 70 53 41 64
45 76 96 56 53 65 53 88 108 93 85 145 139 109 69 92 95 129 123 132
143 169 144 140 163 192 117 112 164 102 66 181 111 100 106 118 102 116 132 100
131 97 80 65 114 125 122 145 122 143 177 176 231 209 224 132 110 127 99 180
164 120 169 115 119 160 121
GRO-B15A 86
66 67 145 233 366 369 283 291 143 265 420 476 456 348 256 179 121 85 75 111
112 145 143 205 223 214 203 293 254 280 212 247 148 159 163 140 104 155 217 157
160 150 154 93 66 108 132 168 205 205 211 143 115 166 146 146 159 170 126 158
107 129 127 152 116 169 153 104 115 128 104 114 84 92 87 87 94 93 98 131
107 166 179 115 117 126
GRO-B15B 86
65 71 159 282 368 372 264 287 126 269 412 490 447 356 246 184 116 85 81 108
110 142 147 199 226 196 207 291 250 256 222 254 142 157 163 138 105 173 212 156
159 151 156 92 67 107 136 165 202 202 214 144 114 171 141 143 167 166 128 156
109 130 124 154 114 170 139 118 110 128 96 121 79 95 85 88 96 103 99 132
107 165 181 105 120 132
GRO-B16A 101
36 76 81 90 74 52 51 37 35 46 61 48 49 68 55 68 76 44 62 88
91 83 67 127 121 92 80 93 104 148 128 88 142 190 131 144 139 118 82 98
114 102 98 133 140 156 179 208 186 133 87 59 86 129 116 108 99 88 117 122
134 150 148 121 81 82 64 113 132 88 81 70 78 93 94 93 110 109 172 299
223 252 262 176 217 308 427 433 488 292 196 212 215 274 258 239 204 144 161 174

231
GRO-B16B 101
38 73 77 94 73 58 43 33 37 51 60 52 46 68 49 76 66 48 68 87
91 73 74 122 126 97 76 86 106 148 129 85 140 187 137 131 137 114 88 100
108 107 102 138 140 147 175 210 189 138 83 64 87 132 117 104 91 95 119 119
127 151 151 118 85 76 69 113 127 92 84 83 74 92 98 98 108 110 169 296
222 247 266 174 211 292 402 423 480 296 200 211 210 276 264 241 201 150 157 168
239
GRO-B17A 61
226 220 161 170 244 201 174 135 105 113 138 166 137 110 98 156 163 186 162 187
146 122 113 88 127 132 128 117 107 114 126 96 106 141 121 143 221 201 165 148
146 171 176 185 234 227 187 103 109 100 114 114 101 98 79 117 91 84 153 138
185
GRO-B17B 61
213 220 163 174 206 193 202 144 98 119 136 154 141 115 92 141 171 194 168 170
147 129 114 81 130 129 131 121 113 106 128 94 105 140 121 153 236 201 156 149
146 158 179 181 230 236 189 101 114 105 117 115 102 106 83 116 92 86 159 139
210
GRO-B18A 110
208 267 207 226 320 288 210 254 182 218 170 132 144 161 179 137 222 207 155 270
173 344 303 232 235 213 146 118 219 180 213 186 209 253 198 196 209 212 137 182
152 210 245 166 256 231 140 169 197 245 223 118 89 103 90 109 126 144 148 159
181 190 162 141 146 146 98 92 95 116 80 103 83 89 83 109 133 141 111 124
131 147 148 144 117 79 59 87 113 134 137 127 132 137 117 138 83 92 63 62
66 76 90 87 99 115 71 88 79 70
GRO-B18B 110
213 259 253 224 298 276 207 249 184 212 171 121 138 159 179 142 217 204 150 273
169 346 298 229 235 215 155 134 190 167 215 156 204 294 189 193 207 213 126 182
151 205 248 159 256 226 143 165 190 253 207 128 78 109 92 107 120 148 145 153
182 191 155 142 148 142 105 76 82 123 79 92 87 86 84 115 147 143 112 119
137 139 153 144 115 77 65 76 116 127 128 129 140 126 122 145 83 90 64 60
73 70 87 81 100 122 71 91 71 66
GRO-B19A 57
119 90 155 214 227 309 282 184 215 285 210 287 197 188 157 133 73 120 106 88
118 120 107 180 166 153 189 133 135 173 188 246 263 308 232 233 176 165 228 176
167 157 127 98 186 118 136 116 119 136 136 150 188 143 162 162 195
GRO-B19B 57
116 83 157 217 232 304 308 181 220 284 213 274 195 190 150 138 77 115 112 87
121 127 93 192 180 165 205 137 145 171 212 245 265 309 229 238 183 160 237 176
170 162 119 94 181 120 147 120 117 140 131 146 189 140 173 154 169
GRO-B21A 105
117 122 129 132 155 110 118 97 98 110 185 175 118 106 138 108 165 140 109 112
190 153 137 119 148 206 185 148 141 174 230 209 160 168 249 142 184 177 125 137
121 133 120 181 195 217 202 209 223 204 219 170 172 137 134 164 160 125 149 157
176 220 216 230 144 145 131 130 179 177 119 127 92 81 128 83 89 91 96 108
105 101 102 112 98 87 90 90 94 99 96 86 103 127 108 105 105 125 114 100
91 89 124 154 127
GRO-B21B 105
111 114 132 136 146 109 123 77 96 117 188 181 118 112 136 102 168 146 111 111
191 152 139 121 151 203 174 148 140 174 233 207 161 168 246 147 189 178 143 134
126 127 131 182 208 220 209 218 224 207 215 173 160 159 134 159 150 131 156 157
176 222 210 240 143 149 131 127 179 179 117 122 94 88 126 81 93 90 99 104
107 103 98 114 99 88 90 85 94 102 90 87 109 121 117 103 102 125 113 105

88 84 133 153 125
GRO-B22A 144
527 321 268 159 166 156 268 179 286 315 245 295 295 347 273 257 201 249 281 250
193 208 135 191 137 161 140 245 137 132 304 252 190 204 211 208 118 135 138 218
224 194 151 161 170 94 67 55 65 59 48 44 34 67 91 72 75 90 97 129
90 32 98 74 90 97 93 85 54 46 40 58 33 43 42 75 73 72 75 63
55 45 65 72 57 79 43 41 49 63 37 37 40 34 33 57 56 68 44 39
36 35 35 43 29 26 33 34 30 37 56 80 55 38 50 39 66 73 54 62
100 73 75 73 46 39 60 60 66 62 65 83 88 105 87 91 74 61 56 52
115 80 92 64
GRO-B22B 144
534 314 266 177 162 163 265 172 291 311 250 280 297 345 262 250 203 248 290 253
193 213 135 195 139 164 145 238 134 145 305 256 185 202 214 207 117 138 134 218
227 196 148 162 171 85 67 60 61 62 46 40 40 63 89 70 85 86 98 129
88 30 99 76 89 98 97 83 51 48 37 62 33 39 48 73 67 78 74 59
50 45 67 75 55 78 44 42 46 65 33 38 43 52 42 31 56 69 41 38
36 33 39 33 36 28 32 38 26 45 32 83 49 37 50 37 66 77 57 64
87 79 85 63 40 38 67 60 64 63 63 91 77 119 75 97 76 60 49 59
111 78 93 59
GRO-B23A 100
107 172 153 114 138 165 177 118 125 126 108 105 67 79 76 93 101 85 67 43
34 60 90 113 69 63 94 49 77 68 39 55 94 100 87 55 100 122 87 68
74 102 118 115 67 109 177 123 131 139 84 63 76 92 134 105 144 174 177 187
188 161 134 81 50 79 102 108 100 106 110 123 175 158 180 177 128 77 80 61
152 202 128 112 116 80 106 105 94 113 104 196 376 219 214 226 176 232 252 322
GRO-B23B 100
113 167 147 95 133 161 176 123 126 117 120 100 68 79 74 99 103 85 74 48
43 55 93 114 67 57 92 55 74 67 46 47 89 100 82 65 84 124 74 59
73 97 125 121 71 116 166 121 133 135 75 71 66 98 136 101 154 174 176 186
193 152 137 77 54 76 106 104 97 116 105 124 179 149 187 176 126 76 78 64
155 200 119 118 117 79 109 107 95 107 111 189 379 223 216 223 164 257 250 320
GRO-B24A 139
106 113 185 144 69 106 102 134 137 175 175 131 104 86 78 123 101 59 120 109
140 141 103 125 94 164 152 102 106 100 87 94 104 75 75 85 66 75 112 105
101 60 43 96 50 97 87 62 54 110 109 86 59 85 130 67 60 85 59 116
75 64 80 151 92 110 87 64 64 125 86 112 94 121 141 114 112 123 148 127
53 92 91 99 80 103 78 72 110 83 121 142 104 89 69 75 63 96 100 64
70 101 77 99 61 39 62 85 67 90 113 99 112 101 123 99 96 100 135 200
87 98 113 118 84 142 104 93 103 130 95 158 151 158 286 267 237 207 170
GRO-B24B 139
136 119 203 154 77 114 110 142 154 249 179 126 112 85 98 97 102 69 126 115
138 133 105 143 82 164 155 109 111 93 82 107 113 73 72 79 52 81 125 110
113 49 48 104 49 96 92 65 53 95 97 75 66 90 126 66 54 88 66 106
70 64 83 153 98 113 89 62 68 128 83 113 83 124 142 114 114 120 149 120
55 92 93 94 87 101 76 73 112 82 132 146 93 102 66 81 64 92 111 64
75 91 76 101 64 33 68 80 79 88 108 102 111 107 117 96 87 111 137 197
92 98 112 111 76 153 105 87 107 130 96 152 157 155 286 265 234 207 176
GRO-B26A 88
222 241 371 237 203 238 261 241 226 210 138 199 225 284 321 269 219 249 155 141
259 194 133 110 83 223 128 200 157 169 187 228 194 136 120 169 173 181 231 179
194 87 86 92 97 168 112 174 208 157 167 149 113 112 125 119 152 164 136 133
120 206 221 131 121 88 87 108 183 201 78 105 151 119 210 148 105 148 231 166
167 163 203 261 145 151 164 200

GRO-B26B 88
217 238 327 237 195 237 255 269 228 216 149 203 216 297 308 283 222 243 157 145
257 200 137 108 89 223 122 220 158 167 184 231 201 132 122 162 169 191 230 173
195 91 84 91 98 168 117 170 191 180 177 151 124 110 127 129 141 156 122 133
123 207 220 132 121 87 89 104 184 202 79 102 150 110 214 143 106 149 224 171
167 157 194 256 140 159 160 208
GRO-B27A 140
286 183 229 310 265 205 139 80 272 171 265 219 206 242 299 228 178 147 216 229
223 267 210 168 113 97 133 116 196 138 209 154 176 162 152 150 227 167 161 140
173 101 118 205 148 137 108 93 89 115 168 152 143 71 78 177 130 135 111 85
138 139 116 105 105 183 152 62 86 92 153 134 49 31 42 48 36 46 39 53
51 45 36 39 38 43 47 68 52 70 59 46 74 45 73 89 69 36 43 49
34 69 117 73 74 73 46 46 30 41 56 34 46 42 52 55 52 52 100 50
74 91 62 40 28 50 78 70 91 80 93 110 108 84 77 93 97 85 114 76
GRO-B27B 140
301 189 205 319 246 215 130 82 285 169 266 219 209 241 302 236 178 158 200 235
229 272 212 167 111 98 134 120 199 143 210 156 179 166 161 151 226 174 154 150
160 111 122 219 144 145 111 95 91 115 165 149 141 77 78 180 131 136 110 93
132 138 120 109 101 181 158 64 88 89 156 133 49 36 43 43 36 49 41 51
52 43 37 44 33 49 43 68 59 66 58 50 72 44 79 86 69 43 37 47
40 69 127 75 75 70 49 48 34 40 56 37 44 39 53 58 53 50 101 54
73 99 60 42 27 50 80 82 87 75 96 117 107 87 71 94 93 85 106 79
GRO-B28A 94
104 133 73 97 71 85 91 106 147 155 157 119 104 146 124 121 111 168 142 131
101 89 108 68 71 58 58 111 84 102 100 123 115 84 92 74 76 58 48 87
100 103 89 111 93 73 85 68 94 155 97 94 113 136 125 110 100 87 154 165
142 152 149 209 105 93 101 114 139 130 127 153 198 161 241 202 165 154 163 149
138 164 213 163 140 147 131 157 137 128 129 141 94 117
GRO-B28B 94
101 135 76 98 69 85 90 99 152 158 157 120 104 150 122 117 113 173 140 126
103 91 104 75 68 52 70 93 90 97 107 123 113 91 92 80 73 54 60 81
108 103 101 103 95 71 82 67 101 154 94 101 120 123 135 111 98 88 162 180
134 160 138 211 107 98 100 123 150 135 101 153 201 156 234 202 160 159 163 161
142 145 205 176 133 143 126 160 144 132 114 142 94 118
GRO-B29A 58
115 163 154 69 127 163 134 254 262 170 132 243 274 219 265 307 288 288 246 228
309 200 160 128 190 162 182 171 155 186 183 206 248 186 216 160 135 159 175 308
241 139 129 127 138 188 128 132 173 176 219 248 178 166 152 138 149 109
GRO-B29B 58
115 164 151 54 127 160 143 250 255 172 131 245 272 219 257 318 272 294 243 240
293 213 154 123 184 155 181 172 152 188 188 198 251 207 212 157 138 161 173 310
233 143 122 131 136 186 125 127 180 173 225 245 180 164 155 142 145 106
GRO-B30A 75
422 284 298 151 211 166 219 232 177 144 155 103 190 172 148 139 180 199 172 96
119 154 126 114 108 86 80 71 80 102 146 230 127 131 183 97 103 88 208 281
176 144 122 81 72 50 52 74 123 90 82 118 104 121 98 91 110 172 160 113
187 165 189 105 105 122 146 198 186 144 211 266 226 288 267
GRO-B30B 75
409 287 297 152 206 174 216 234 189 122 114 86 183 173 154 135 173 202 175 105
116 124 121 118 106 103 76 70 87 100 142 215 132 129 163 98 104 89 209 289
189 142 104 76 73 48 48 77 127 94 88 111 105 122 102 89 113 167 147 115
181 162 190 96 114 121 146 206 175 146 217 272 220 295 251
GRO-B31A 83

319 222 182 162 111  97 108 140 120  84 107 137 171 125 155 183 157 198 178 132
123 216 219 197 138 147 195 141 165 115 119 101  96 110 143 161 119 143 134 102
96 111 155 139 134 183 177 166 152 159 170 147 142 132 143 124 139 123 115 126
101 121 129  94  87  63  50  45  47  54  67  56  51  55  57  69  50  57  56  60
65  84 100
GRO-B31B 83
318 220 187 159 114  92 115 146 121  85 109 143 183 116 148 186 173 181 189 129
122 202 226 204 133 144 188 138 166 116 109 109  98 101 141 153 123 142 139  95
104 122 150 117 137 189 182 162 156 160 171 146 136 134 147 124 135 139 105 115
92  86 105 115  89  62  52  44  53  53  60  60  47  57  57  70  51  54  58  61
68  90  91
GRO-B32A 92
441 365 343 241 323 268 257 334 297 372 301 254 245 276 213 241 230 261 295 243
233 181 197 219 189 225 207 118 137  89 125 148 180 213 213 179 155 190 179 199
186 195 230 200 201 166 134 111 129  93 145 129 202 184 188 165 205 173 130 115
149  90 125 110  98 152 149 130 132 119  83 118 107 170 149  96  63 136 120 127
155  64 135 180 172 204 132 132 184 154 110 138
GRO-B32B 92
441 355 366 228 322 271 255 337 293 364 297 261 241 268 216 245 222 254 294 234
207 189 194 240 201 227 216 117 136  93 137 141 183 207 207 179 157 190 173 209
184 206 215 197 191 159 122 122 121  83 154 129 185 190 192 167 200 170 132 139
123  97 126 109 107 148 155 132 141 116  83 126 103 164 151 105  68 127 122 129
150  79 130 178 172 217 129 141 181 156 110 151
GRO-B33A 63
93 106 132 154 212 207 191 197 172 182 124 165 239 168 204 167 147  98 114  81
97 125 148 156 157 177 197 139 155 133 144  93 110  88 103 113 124 119 123 103
76  94  88 121 149 127  95 120 101 124 136  62 126 126 133 162 134 183 169 133
108 147 157
GRO-B33B 63
106 119 130 157 204 204 181 189 170 174 126 175 217 171 199 147 150  91 119  82
102 112 159 153 164 178 192 136 145 127 135  97 101  93  89 136 136 115 119 113
71  97 101 124 149 113  83 119 112 136 135  68 115 128 144 158 133 179 178 141
112 138 161
GRO-B36A 47
417 420 327 312 377 224 199 224 166 205 325 259 263 163 129 197 236 185 157 108
150 229 182 244 237 236 269 234 271 271 265 281 267 211 131 144 144 158 148 125
200 153 114 115 128 192 214
GRO-B36B 47
425 425 322 322 347 233 193 232 164 221 307 250 258 171 139 198 240 191 164 113
152 230 180 245 241 232 268 246 263 268 269 277 256 219 136 147 146 160 143 126
193 152 110 119 135 194 216
GRO-B37A 69
113  81 190 142 226 233 156 168 233 188 255 181 215 402 229 240 150 333 325 270
156 247 227 190 282 179 155 122 161 160 161 164 174 195 206 221 182 203 178 124
126 152 117 154 156 174  85 184 159 209 258 207 169 122 128 129 236 169 151 153
220 175 245 180 165 227 265 230 294
GRO-B37B 69
122  84 202 142 219 237 152 168 224 184 222 204 218 395 227 233 152 330 321 269
137 228 217 192 272 174 156 114 174 151 172 168 175 204 207 219 183 199 181 130
121 147 122 161 159 176  88 189 157 210 255 210 165 126 124 133 236 170 149 154
221 176 241 184 157 233 262 233 292
GRO-B38A 71
471 414 241 184 184 211 141 241 286 252 309 168 244 213 238 216 287 260 204 157

135 137 163 146 163 189 150 156 149 146 226 141 168 216 165 163 148 83 100 183
152 142 125 153 256 149 111 110 166 198 168 142 181 206 141 166 139 136 127 136
146 167 191 148 194 129 125 134 180 169 121
GRO-B38B 71
468 410 246 183 191 218 151 248 279 273 300 184 249 201 242 198 267 256 200 173
146 136 138 148 169 186 147 168 139 136 226 142 159 222 147 168 137 84 99 171
166 148 115 154 239 153 115 113 158 199 160 147 184 204 137 168 145 130 132 132
143 173 189 155 191 127 128 133 182 169 121
GRO-B39A 126
158 176 179 158 174 129 133 180 204 143 195 160 118 138 110 78 161 144 133 102
81 143 111 108 97 85 81 64 79 72 87 93 109 118 108 95 97 70 42 52
83 65 67 128 97 76 97 68 105 104 119 96 85 80 94 99 97 86 89 95
73 64 50 105 101 81 51 48 89 57 89 76 64 74 76 83 82 44 79 105
87 66 74 101 110 82 85 82 105 71 61 45 63 75 81 61 66 94 74 75
83 85 88 117 102 83 51 112 101 91 93 74 98 102 82 112 91 85 83 66
84 73 102 90 67 57
GRO-B39B 126
173 179 178 155 151 128 127 185 198 148 186 155 120 139 105 82 158 137 134 112
71 143 115 114 91 81 85 69 84 81 72 91 112 115 109 106 81 73 52 41
72 63 63 127 99 78 97 71 95 114 121 85 94 94 93 94 92 94 74 122
75 68 57 98 97 89 47 51 88 56 89 81 59 70 78 83 77 47 79 103
88 65 72 102 109 83 84 84 106 68 59 46 68 70 83 59 69 91 76 70
84 85 88 124 98 86 44 113 105 91 94 82 88 107 86 104 90 85 83 68
81 77 93 98 69 57
GRO-B40A 63
414 391 558 489 551 388 341 229 181 169 99 107 122 211 165 125 94 137 218 152
258 228 229 345 291 200 131 114 137 201 256 278 314 194 346 391 230 194 148 165
155 263 259 264 176 148 119 137 163 151 224 219 265 201 223 199 213 234 172 139
165 197 275
GRO-B40B 63
420 391 552 497 543 373 349 226 182 171 105 120 110 193 144 125 100 132 217 156
248 236 239 337 294 215 126 121 136 196 247 277 311 196 348 393 226 200 146 158
161 288 260 244 183 147 117 135 170 148 220 219 272 198 223 202 213 225 187 139
176 179 262
GRO-B41A 74
129 169 127 125 222 194 157 147 120 102 93 126 149 162 158 220 255 197 182 126
197 268 248 316 158 161 149 141 148 124 121 134 125 165 166 202 153 150 159 161
154 158 80 64 102 131 107 118 125 164 99 80 75 96 84 73 76 102 132 99
103 107 80 63 67 57 67 88 91 92 95 99 83 108
GRO-B41B 74
144 161 129 124 222 202 161 142 122 107 86 123 153 165 154 209 233 193 165 121
193 265 234 316 148 174 155 134 147 124 127 131 123 165 167 203 151 151 162 159
159 163 78 61 103 136 108 113 128 163 95 86 72 93 81 81 69 102 133 100
101 110 80 69 58 65 67 90 88 96 95 100 88 99
GRO-B42A 103
110 112 86 55 61 59 77 94 100 105 57 55 37 48 62 47 43 70 49 68
94 91 98 77 85 87 82 69 45 69 97 84 71 69 58 48 64 83 93 86
50 51 62 43 87 74 74 58 70 122 87 56 112 92 86 82 99 153 142 107
89 138 181 105 145 96 90 47 84 91 88 80 92 93 114 107 146 142 118 83
84 108 140 146 112 93 107 108 158 171 199 168 145 77 124 89 198 140 117 103
82 139 140
GRO-B42B 103
116 110 87 54 65 58 80 93 98 102 60 50 37 50 62 44 36 73 52 67

99 90 94 73 93 79 83 64 53 68 91 87 72 70 54 55 62 81 94 85
53 53 58 38 89 80 69 57 76 113 100 53 130 91 85 82 104 156 139 102
91 139 183 117 146 100 84 51 87 86 90 81 92 92 117 106 147 139 120 80
86 107 140 145 116 92 106 106 167 166 202 167 145 79 129 86 198 141 123 91
95 128 136
GRO-B43A 99
374 411 220 261 209 175 121 119 125 184 81 120 132 125 95 119 114 106 78 99
88 84 64 92 100 151 127 167 112 110 82 90 107 103 95 89 49 54 48 50
48 44 35 54 60 72 79 74 68 68 85 79 72 79 56 77 73 54 35 46
44 36 45 36 33 57 47 44 48 71 108 99 72 70 115 106 119 78 74 146
58 58 71 62 60 42 63 98 99 73 93 104 76 68 87 100 104 99 149
GRO-B43B 99
386 404 217 259 220 171 121 118 119 176 83 118 130 121 98 123 103 100 74 90
80 83 64 92 110 141 115 158 103 112 81 99 101 99 105 82 57 50 44 52
48 51 42 57 52 65 74 79 73 69 86 85 64 72 58 68 91 52 34 46
46 35 43 36 33 52 52 43 45 76 117 97 70 79 108 109 114 80 76 144
59 60 69 62 59 42 62 100 97 79 86 110 72 70 86 102 108 109 134
GRO-B44A 57
127 89 165 155 186 119 166 152 132 228 184 146 125 123 124 146 131 147 159 141
197 152 153 145 121 126 144 142 159 157 133 96 142 176 176 160 156 133 128 134
148 189 136 130 107 114 125 123 129 99 125 129 136 190 134 187 206
GRO-B44B 57
125 94 166 157 186 117 168 140 145 220 192 148 121 139 123 140 137 142 162 143
203 153 151 141 129 121 138 132 166 157 136 85 136 165 179 152 149 140 131 143
139 185 138 125 100 126 127 119 130 105 122 126 126 181 136 192 205
GRO-B45A 167
103 128 146 149 49 46 50 113 129 190 107 102 62 74 50 95 78 79 254 245
249 167 155 224 99 77 78 181 190 215 325 255 165 192 81 62 108 77 38 37
35 86 73 62 74 81 97 90 65 64 62 75 107 57 81 74 47 40 40 46
43 67 53 91 67 67 93 86 75 62 64 102 92 70 41 50 53 48 42 33
36 21 33 26 29 40 26 27 34 22 35 32 27 28 29 30 33 34 52 46
39 35 35 32 40 43 36 45 53 66 57 65 52 57 49 48 81 57 81 100
111 88 100 82 74 47 31 54 81 59 58 57 54 56 70 69 70 67 61 36
40 35 56 67 46 50 39 42 36 35 44 49 217 309 341 244 191 200 131 205
174 206 269 253 187 132 123
GRO-B45B 167
85 130 148 132 64 48 48 115 135 218 126 99 53 77 51 103 65 82 261 251
246 165 162 216 101 73 83 185 187 205 329 249 166 178 82 65 105 75 39 41
42 79 79 64 82 74 98 92 65 66 56 75 106 60 84 74 50 55 34 45
32 73 49 86 65 68 92 86 66 67 69 100 94 65 50 49 48 47 42 33
35 22 25 30 32 35 23 30 35 22 39 33 27 24 32 27 32 35 54 47
50 30 35 27 52 51 36 45 50 64 58 60 47 54 57 49 74 57 96 121
106 90 102 93 66 56 35 62 74 58 60 57 63 51 74 65 73 73 49 40
44 34 52 65 51 50 43 38 48 40 40 53 214 322 343 253 175 208 132 202
153 219 272 228 187 136 124
GRO-B46A 56
245 269 267 124 132 78 128 117 133 127 133 186 128 158 100 128 132 89 109 93
118 167 153 145 130 127 148 114 112 96 94 119 110 134 163 148 173 167 221 177
162 163 188 178 184 187 227 154 134 106 129 176 141 109 119 175
GRO-B46B 56
233 260 243 122 125 95 105 103 138 120 121 185 122 154 101 122 135 80 107 96
116 167 146 154 131 125 154 121 103 91 90 125 106 142 162 149 176 163 214 177
160 168 182 176 186 191 225 152 134 105 127 176 140 109 114 175

GRO-B48A 48
55 72 135 140 195 220 247 150 197 143 152 173 291 257 296 307 245 203 136 162
155 96 204 235 181 193 176 169 209 222 303 300 263 269 245 254 279 189 148 264
251 153 122 173 290 309 338 229
GRO-B48B 48
61 61 138 132 190 217 244 149 193 145 155 172 306 251 304 317 250 203 142 158
162 95 198 226 192 194 179 164 214 225 297 304 266 263 247 248 278 192 149 262
252 157 122 169 285 317 331 231
GRO-B49A 84
314 295 117 96 123 144 46 55 51 96 201 238 297 234 290 281 289 197 196 86
117 130 179 163 134 194 204 179 223 140 216 194 186 242 224 207 225 163 182 312
274 304 104 51 59 79 98 133 143 222 103 134 116 113 166 223 165 188 211 263
155 163 156 142 215 188 96 87 77 83 66 92 79 150 150 173 154 123 123 132
215 262 173 188
GRO-B49B 84
327 294 123 90 143 139 45 53 49 93 204 248 297 243 284 281 286 205 197 83
129 150 189 168 153 182 211 172 219 141 216 191 191 243 226 202 224 166 189 313
274 304 102 56 55 80 98 132 144 225 103 139 118 114 162 228 166 185 210 254
159 157 158 149 212 191 93 91 82 71 68 86 83 156 158 171 163 120 122 124
219 253 169 199
GRO-B50A 92
101 98 164 162 201 180 157 174 159 132 80 84 57 67 101 94 81 132 210 146
128 155 122 134 184 127 103 92 53 102 192 239 216 134 118 55 81 91 155 165
78 98 91 79 199 170 94 105 110 83 103 90 172 181 96 93 88 133 143 147
76 86 118 74 76 48 47 64 74 59 65 77 96 115 130 102 97 97 98 44
53 93 112 106 105 63 59 86 120 152 151 146
GRO-B50B 92
99 98 170 159 198 178 150 167 170 127 84 73 64 70 111 87 69 133 199 143
128 153 127 133 165 130 97 96 68 97 187 233 212 137 123 48 84 99 146 160
82 99 102 90 204 171 89 100 108 92 92 98 167 186 99 95 92 129 145 141
74 89 118 69 83 49 50 66 74 54 70 73 98 116 133 100 86 97 94 40
57 93 112 91 107 67 63 82 125 152 146 147
GRO-B51A 124
274 298 271 230 252 245 233 281 208 36 38 38 45 49 56 106 84 108 115 86
92 97 105 144 193 147 191 131 74 52 93 134 116 91 95 44 124 106 105 90
93 110 169 112 54 85 114 106 139 134 134 110 76 66 56 61 76 80 87 86
99 118 101 101 69 72 90 52 78 54 62 94 69 52 73 47 53 54 78 65
75 42 64 86 57 78 61 45 44 60 61 43 35 48 84 40 34 50 44 64
44 40 50 91 46 65 65 58 34 52 51 44 42 55 47 52 53 56 61 40
44 35 42 31
GRO-B51B 124
267 293 285 230 249 250 230 281 204 38 40 42 50 44 56 109 88 102 102 78
89 91 122 155 192 149 186 131 77 36 112 142 130 96 98 48 126 99 121 90
105 116 185 120 59 88 115 105 133 134 130 116 70 69 55 60 77 76 89 82
99 117 102 100 65 77 85 60 83 47 54 102 71 58 71 47 50 52 73 67
82 43 58 85 72 75 64 49 44 59 55 48 36 46 84 40 34 48 46 64
41 45 49 91 47 65 63 56 39 49 50 41 47 56 44 51 55 55 60 47
40 33 40 37
GRO-B52A 75
347 342 312 342 340 352 353 308 244 365 319 428 458 341 466 370 379 406 327 329
228 216 195 228 225 219 216 226 203 185 97 50 53 48 33 38 30 20 30 26
34 33 34 34 40 38 29 15 45 50 57 60 36 29 45 39 31 36 46 59
55 60 54 70 71 82 102 103 106 71 74 54 77 97 94

GRO-B52B 75
352 346 313 344 340 353 350 304 244 366 325 429 454 341 468 373 378 407 320 320
240 228 187 235 220 227 216 225 204 185 94 50 58 50 32 33 29 24 34 25
29 31 39 32 41 34 19 24 48 51 55 63 37 30 48 33 31 34 47 60
59 60 50 71 69 85 103 103 103 76 70 57 74 95 108
GRO-B53A 85
216 277 264 265 287 437 246 170 115 80 65 53 57 52 45 88 143 198 161 151
96 83 136 127 128 102 114 109 89 68 68 95 162 85 111 110 154 217 161 97
133 102 145 142 73 68 104 146 138 93 114 156 127 102 91 67 53 62 54 65
138 107 97 85 73 53 82 96 104 94 108 91 100 84 79 90 89 75 62 52
61 66 102 76 81
GRO-B53B 85
169 268 267 259 294 434 248 167 117 80 62 53 59 53 42 92 135 204 160 151
99 85 138 127 131 101 113 109 87 70 65 96 160 94 120 108 162 217 156 101
137 96 160 142 75 67 103 136 147 96 112 158 131 96 95 67 55 65 59 80
114 109 95 91 75 61 79 92 104 91 102 89 97 71 77 93 89 82 55 66
67 73 92 74 97
GRO-B54A 62
183 208 217 155 131 145 146 181 150 215 157 144 126 147 164 103 170 217 181 203
172 127 144 201 258 247 186 250 242 178 216 193 264 214 256 103 90 70 70 80
87 78 86 106 85 75 81 104 73 102 113 113 98 107 99 78 115 107 102 83
57 94
GRO-B54B 62
186 207 211 159 133 147 145 186 150 208 161 134 127 141 163 109 177 209 183 201
183 136 135 205 244 244 190 241 253 175 209 193 267 211 267 104 87 72 66 83
85 79 86 102 90 72 85 99 78 101 115 113 96 104 101 80 110 107 105 85
73 91
GRO-B55A 103
350 329 346 97 30 43 51 80 96 113 133 100 81 104 91 147 203 174 190 176
195 145 155 131 121 173 183 139 109 103 99 103 138 117 162 164 188 170 157 123
113 234 226 156 197 94 102 104 76 98 99 87 118 112 120 132 166 112 131 145
107 119 133 84 64 90 117 106 77 110 131 76 68 63 82 78 64 60 101 105
79 85 84 60 43 62 63 94 104 120 105 107 96 89 121 101 99 87 118 94
79 72 183
GRO-B55B 103
355 325 342 101 27 42 60 79 96 100 126 112 91 104 91 157 208 177 171 183
218 133 161 139 126 171 180 133 115 107 88 118 132 112 165 168 183 169 155 128
114 233 216 163 169 92 101 107 74 100 98 88 115 113 120 128 162 111 134 148
99 122 133 74 62 89 120 105 77 108 131 83 64 62 89 71 70 53 103 106
86 83 84 62 43 64 67 90 105 116 108 113 95 86 122 93 101 87 111 94
88 70 191
GRO-B56A 81
101 176 75 87 163 156 129 225 229 244 149 218 256 275 276 289 204 159 156 123
120 89 119 233 199 274 131 166 130 185 170 244 235 231 176 147 110 77 63 92
113 73 84 92 82 132 63 74 143 112 109 89 78 68 114 133 124 83 131 153
113 79 90 98 96 174 125 205 162 115 147 103 90 85 134 98 131 122 106 119
112
GRO-B56B 81
109 176 82 81 167 148 132 225 226 248 151 209 250 274 271 290 206 161 152 127
120 95 119 235 195 257 139 164 129 176 170 251 235 231 173 151 111 77 65 93
113 81 84 85 67 138 67 79 138 112 112 88 74 76 111 121 128 90 111 162
106 82 86 102 98 174 117 189 170 114 148 97 96 85 135 95 131 125 112 117
94

GRO-B57A 65
190 185 170 253 276 249 231 250 152 90 98 114 127 161 109 108 64 101 123 157
152 149 87 113 127 121 97 139 246 220 249 231 207 161 116 117 113 176 172 198
209 221 243 343 257 169 237 199 166 196 187 140 246 214 212 231 181 124 152 249
204 308 145 105 214
GRO-B57B 65
191 189 175 234 275 240 237 253 156 81 103 106 133 151 123 96 67 96 126 155
150 145 84 111 125 131 103 124 246 218 247 231 204 165 118 120 110 180 179 199
203 225 242 335 263 155 236 198 173 198 181 136 247 218 201 240 183 123 153 250
203 314 144 108 204
GRO-B58A 102
97 107 151 175 137 140 168 163 117 86 54 52 57 55 71 67 129 107 130 129
111 90 79 87 86 98 95 75 73 63 53 44 49 57 51 46 54 55 63 62
89 209 103 118 112 66 41 61 57 50 48 37 67 68 52 51 54 53 43 58
66 81 97 79 95 73 79 79 95 93 85 115 94 98 122 124 133 150 101 102
115 125 123 133 87 106 109 106 108 76 88 104 114 116 123 129 116 149 132 178
226 294
GRO-B58B 102
85 125 166 174 157 157 160 186 127 84 64 45 60 57 69 60 122 122 127 125
93 88 86 101 76 95 96 73 79 66 53 46 49 57 54 47 66 54 69 59
106 232 100 128 104 77 44 56 64 50 52 45 70 64 49 63 47 39 53 53
66 83 91 90 86 73 80 86 96 91 86 121 87 98 122 129 131 160 99 103
126 122 117 139 94 105 99 112 106 79 86 109 119 117 124 137 114 110 110 181
230 300
GRO-B59A 93
184 197 110 124 216 173 272 182 175 168 177 232 267 232 238 222 197 209 239 212
258 288 238 278 225 246 247 285 377 347 366 226 171 187 128 102 152 155 233 214
211 215 206 172 182 196 221 226 208 173 165 144 160 109 160 188 133 146 161 93
147 89 100 121 90 126 118 91 68 76 100 101 115 128 162 111 78 102 99 70
82 106 133 156 141 143 122 138 106 155 162 151 149
GRO-B59B 93
186 195 106 132 213 175 245 220 183 173 184 223 256 222 244 234 194 199 237 219
258 295 227 254 249 244 253 275 418 354 375 245 170 189 122 111 147 161 243 214
213 222 201 173 189 209 214 224 200 188 163 147 161 115 151 189 131 161 162 92
142 98 101 121 90 126 114 86 77 60 107 98 129 125 165 115 88 99 96 79
88 102 139 159 151 142 121 136 123 146 162 148 162
GRO-B61A 140
242 315 202 173 200 249 130 92 70 84 134 150 95 145 105 103 95 95 69 91
121 182 238 197 199 235 176 181 128 104 85 79 127 223 222 199 117 97 73 97
90 76 72 64 66 47 48 45 70 48 66 70 77 81 82 100 78 114 122 143
79 95 64 35 42 42 50 72 80 94 96 127 146 105 163 132 141 90 63 64
77 89 86 91 69 59 58 62 103 120 75 71 86 57 80 79 64 41 72 91
72 58 77 103 67 82 79 65 94 116 75 69 81 83 70 99 72 53 50 54
52 54 80 83 88 102 103 114 126 86 53 78 94 114 116 87 137 141 138 153
GRO-B61B 140
222 326 208 182 209 251 135 90 74 81 131 144 99 144 113 97 96 96 67 82
130 181 233 204 201 230 179 181 132 100 88 80 127 224 222 198 132 100 72 101
86 80 66 66 65 46 49 40 66 51 69 66 78 75 86 97 83 108 118 149
71 92 60 37 49 42 44 73 72 109 93 143 130 104 162 142 143 79 63 67
82 88 96 89 67 66 52 65 101 128 70 75 86 62 72 77 69 45 67 85
71 64 78 96 80 79 79 68 93 115 74 76 81 77 74 99 73 55 46 56
53 48 86 81 86 108 102 112 116 81 62 79 94 129 124 88 143 131 139 158
GRO-B62A 92

93 83 117 126 95 187 204 124 128 159 184 129 87 88 74 113 141 153 179 159
147 124 92 150 182 167 162 142 91 111 123 129 137 175 107 161 183 118 102 98
146 160 136 149 133 143 174 84 75 68 86 128 154 97 78 127 112 85 79 58
78 72 57 81 70 56 53 40 60 104 81 82 69 55 41 49 54 77 98 100
92 85 62 87 87 78 91 72 79 80 114 98
GRO-B62B 92
93 85 113 121 101 187 203 133 127 160 186 129 85 85 82 110 151 153 173 160
147 126 87 150 172 175 156 145 88 97 129 137 133 175 107 161 191 117 89 99
139 160 150 146 132 146 179 76 74 71 84 131 153 92 79 131 107 84 78 56
78 75 50 90 70 48 60 45 60 95 85 80 79 54 42 47 56 71 105 104
88 74 73 80 88 78 90 71 78 85 100 107
GRO-B64A 84
202 141 139 164 195 215 213 281 216 291 264 265 177 234 108 117 133 138 179 274
303 265 225 226 325 234 326 231 144 127 122 139 176 305 307 216 236 250 237 190
165 197 167 150 92 133 156 162 199 179 166 177 115 113 158 150 151 148 106 165
99 84 71 93 94 89 96 88 93 67 58 54 80 59 83 76 56 56 53 44
67 73 63 74
GRO-B64B 84
190 146 127 161 190 214 217 277 226 285 268 258 173 232 121 109 139 132 178 268
310 261 228 217 327 238 332 230 141 134 114 136 172 308 308 217 256 234 244 196
151 201 155 150 103 120 156 168 226 149 160 173 116 107 156 154 156 151 102 161
101 77 82 92 89 97 97 88 90 64 60 54 80 59 85 77 58 52 55 43
57 83 62 76
GRO-B65A 91
104 126 96 83 60 95 85 89 128 118 124 146 106 117 135 179 182 84 79 79
101 106 92 106 94 77 51 39 90 134 152 39 46 76 51 88 62 62 65 81
111 93 83 76 108 65 47 49 66 98 94 83 70 115 107 73 72 85 63 83
82 96 85 117 109 102 132 94 116 104 51 74 113 112 95 86 47 70 84 62
76 81 111 84 61 77 63 102 122 75 100
GRO-B65B 91
115 118 101 79 63 94 84 54 113 123 123 130 128 129 123 166 178 98 82 73
105 92 100 96 95 82 48 50 87 140 142 58 44 69 57 88 75 55 73 79
115 86 80 72 117 63 50 46 64 99 76 80 69 112 101 81 77 86 55 87
86 96 85 115 102 111 110 94 110 104 56 80 110 118 100 85 64 66 79 67
74 86 104 85 64 78 62 87 118 81 99

# APPENDIX: TREE-RING DATING

## The Principles of Tree-Ring Dating

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

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

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

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

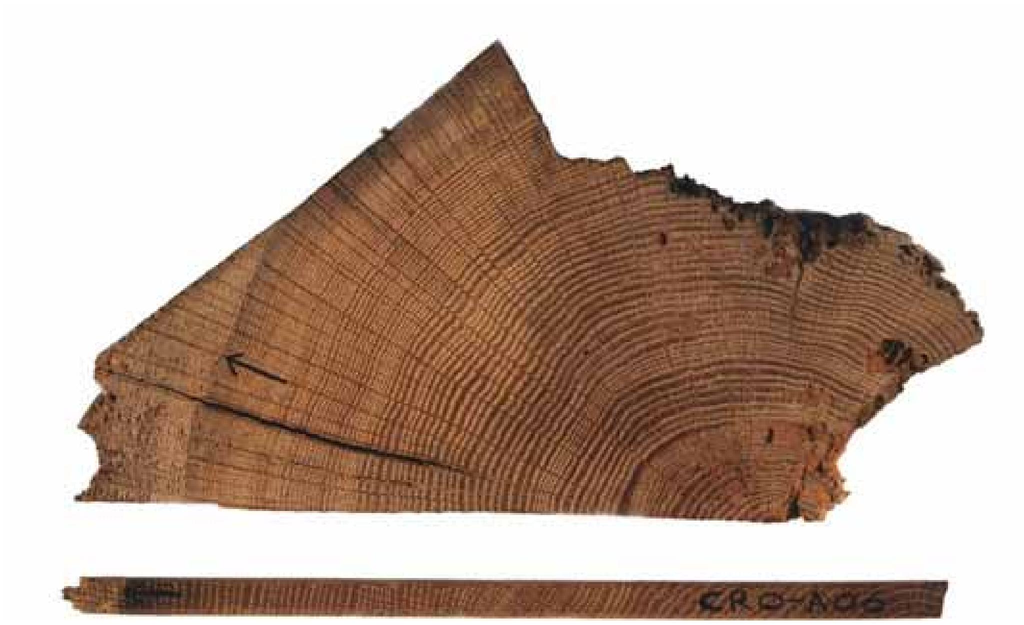


*Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil*

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


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

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

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

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

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

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

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

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

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

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

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

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

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

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

*t*-value/offset Matrix

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

Bar Diagram

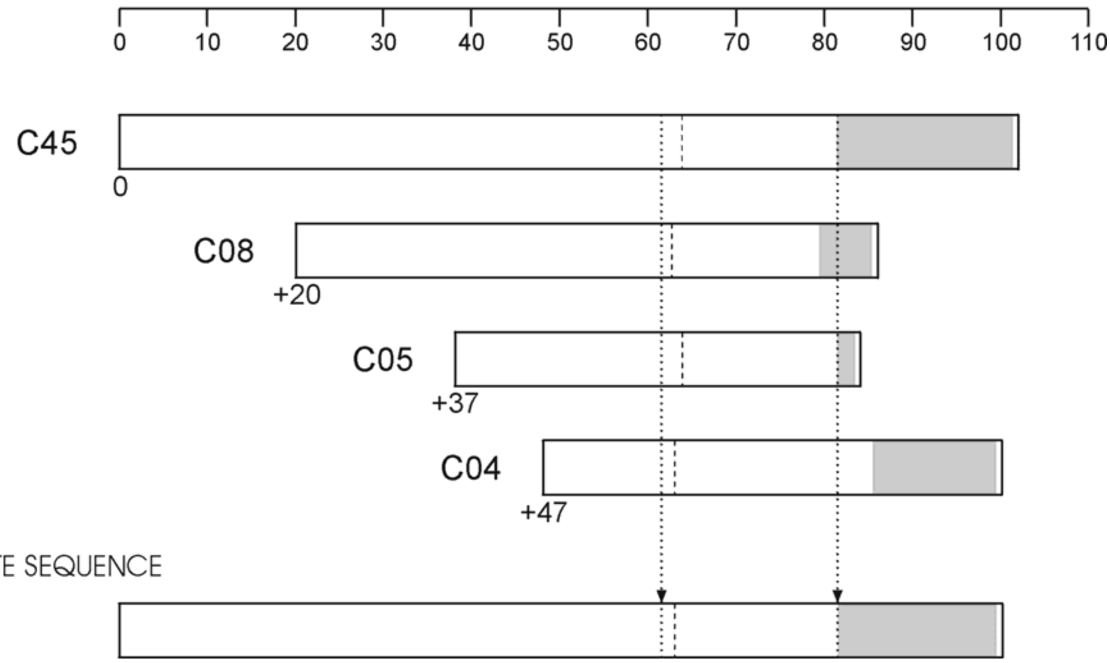



*Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them*

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.

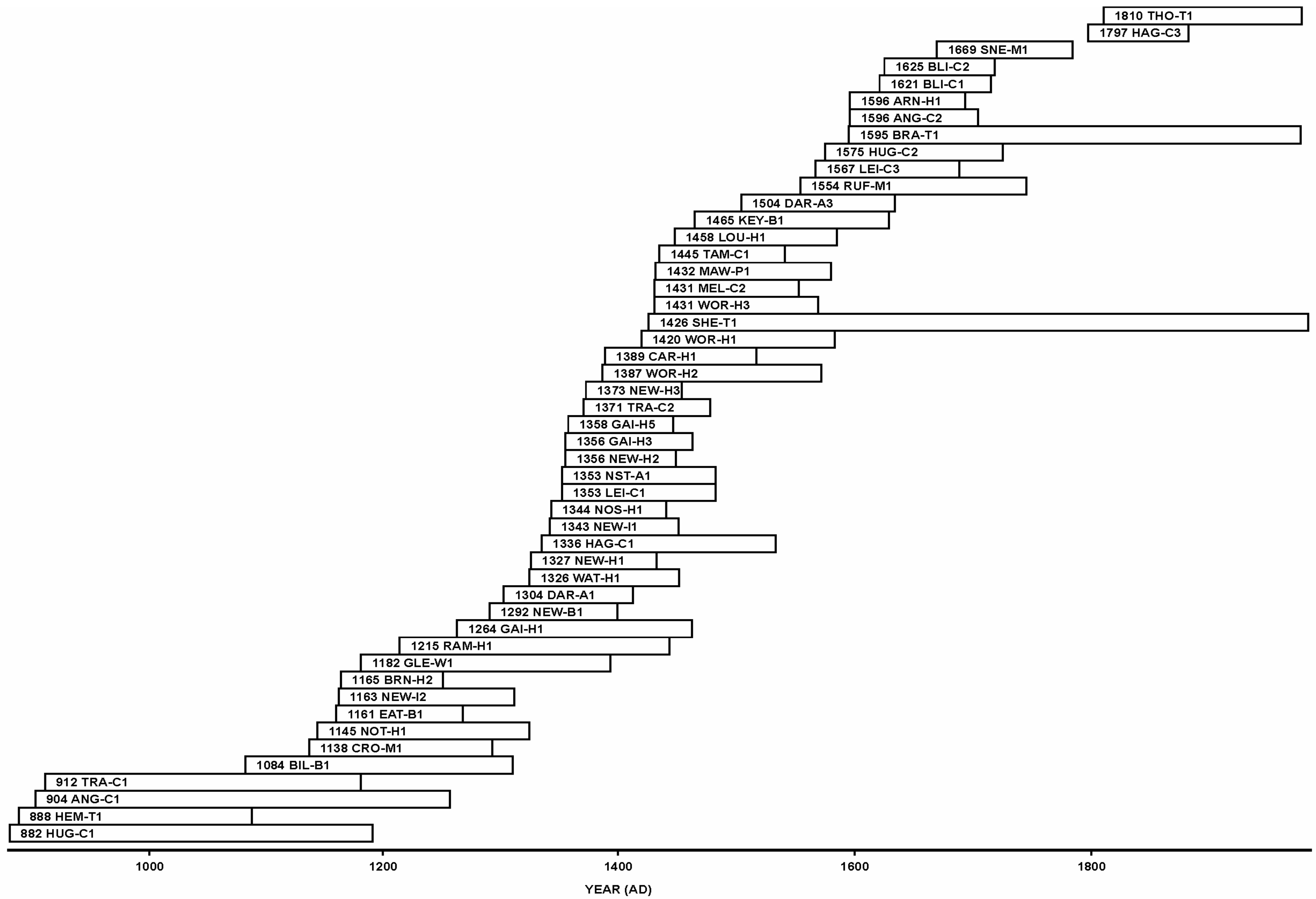
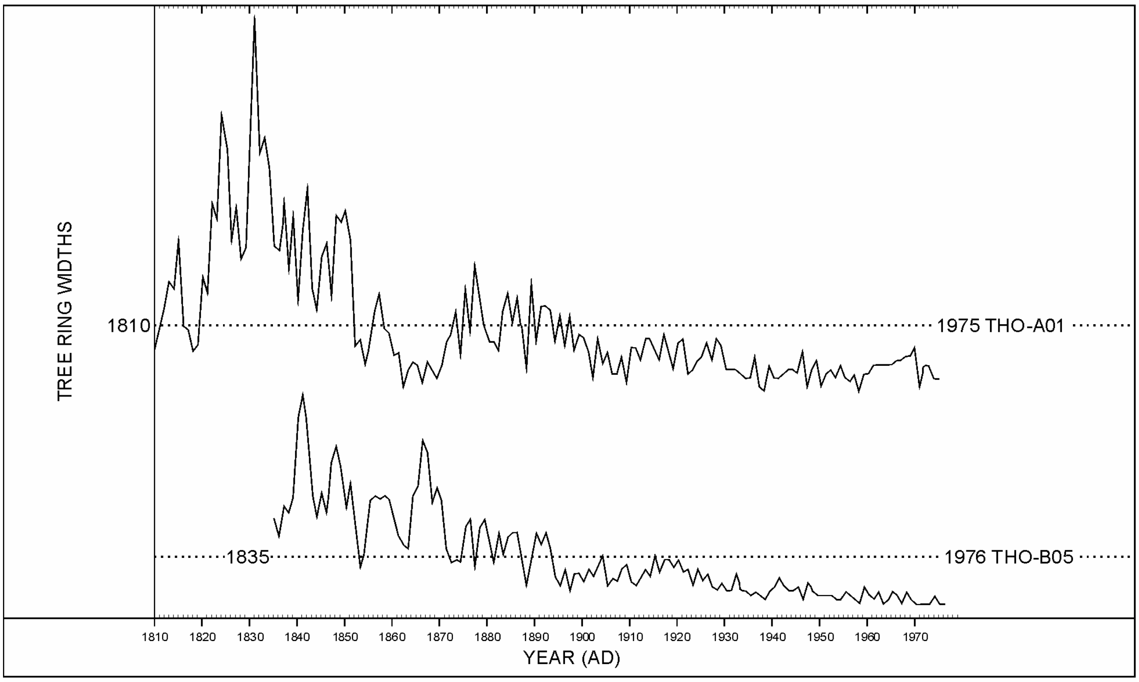



*Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87*

(a)




(b)

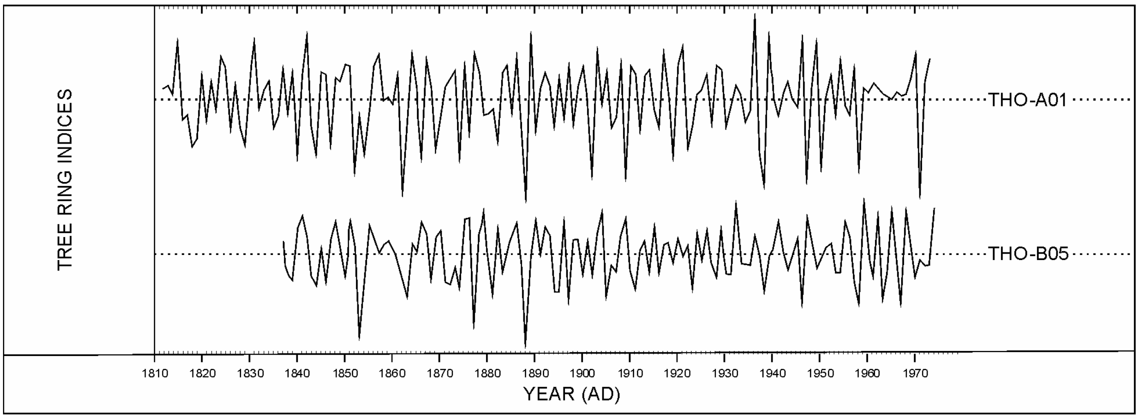



*Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known*

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

Hillam, J, Morgan, R A, and Tyers, I, 1987 Sapwood estimates and the dating of short ring sequences, *Applications of tree-ring studies*, BAR Int Ser, **3**, 165–85

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

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

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, *P A C T*, **22**, 25–35

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

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

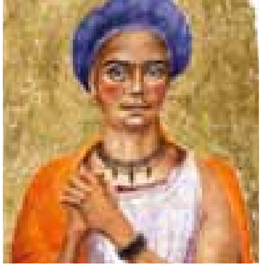
Laxton, R R, Litton, C D, and Howard, R E, 2001 *Timber: Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, 7

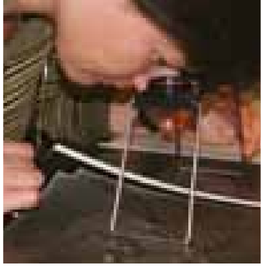
Litton, C D, and Zainodin, H J, 1991 Statistical models of dendrochronology, *J Archaeol Sci*¸ **18**, 29–40

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

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

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


## ENGLISH HERITAGE RESEARCH AND THE HISTORIC ENVIRONMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for the protection and sustainable management of the resource, and to promote the widest access, appreciation and enjoyment of our heritage. Much of this work is conceived and implemented in the context of the National Heritage Protection Plan. For more information on the NHPP please go to http://www.english-heritage.org.uk/professional/protection/national-heritage-protection-plan/.

The Heritage Protection Department provides English Heritage with this capacity in the fields of building history, archaeology, archaeological science, imaging and visualisation, landscape history, and remote sensing. It brings together four teams with complementary investigative, analytical and technical skills to provide integrated applied research expertise across the range of the historic environment. These are:

* Intervention and Analysis (including Archaeology Projects, Archives, Environmental Studies, Archaeological Conservation and Technology, and Scientific Dating)
* Assessment (including Archaeological and Architectural Investigation, the Blue Plaques Team and the Survey of London)
* Imaging and Visualisation (including Technical Survey, Graphics and Photography)
* Remote Sensing (including Mapping, Photogrammetry and Geophysics)

The Heritage Protection Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support community engagement and build this in to our projects and programmes wherever possible.

We make the results of our work available through the Research Report Series, and through journal publications and monographs. Our newsletter *Research News*, 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.english-heritage.org.uk/researchreports

*For further information visit www.english-heritage.org.uk*

ENGLISH HERITAGE

ISSN 2046-9799 (Print)
ISSN 2046-9802 (Online)