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ST LEONARD'S CHURCH
MAIN STREET
APETHORPE
NORTHAMPTONSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Four phases of felling have been detected amongst the samples from St Leonard's Church. The earliest is that represented by samples from tiebeams of the north and south aisles, plus two king-posts in the chancel roof. These timbers have an estimated felling date in the range AD 1412–37.

A second phase of felling is represented by samples from the chancel, notably the cranked tiebeam and four moulded common rafters. These timbers have a felling date in the range AD1611–36.

This early seventeenth-century roof appears to have been replaced in the late-seventeenth century by the present roof, comprising the two king-post trusses with straight tiebeams, these timbers having an estimated felling date in the range AD 1675–1700.

A fourth and final phase of felling is represented by a further, individually dated sample from the chancel. This timber has an estimated felling date range AD 1737–62. It is possible that it represents a phase of minor repair to the roof.

Three site chronologies have been created from the material sampled here, APTCSQ01, SQ02, and SQ03 of six, seven, and six samples, with 193, 139, and 87 rings, these dated as spanning the years AD 1211–1403, AD 1458 –1596, and AD 1579–1665, respectively.

CONTRIBUTORS

Alison Arnold and Robert Howard

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INTRODUCTION

St Leonard's church lies towards the east end of the village of Apethorpe (TL 025 957, Figs 1 and 2) to the north-east of Apethorpe Hall, former seat of the Earls of Westmorland. The fabric of the church is dated stylistically to the late-fifteenth and early-seventeenth centuries, though a single chevron voussoir, reset in the facing of the north aisle, is a possible hint that an earlier structure may have stood on the site.

The building comprises a west tower, a nave flanked by aisles to north and south, a south porch, and a chancel with a chapel attached to its south side. This southern chapel, known as the Mildmay Chapel, contains one of the finest and most imposing seventeenth-century tombs in England: that of Sir Anthony Mildmay, attributed to the sculptor Maximilian Colt and known to have been built in AD 1621.

THE ROOFS

The nave and aisle roofs

The nave roof of St Leonard's church (Fig 3a) comprises four principal rafter with tiebeam trusses (the principal rafters hidden above the nave ceiling), the tiebeams being steeply cambered and supported at each end by short wall posts and knee braces, both of which rise from stone corbels. The tiebeams, posts, and the braces are all given moulded decoration.

Between each truss may be seen intermediate, cambered, lateral, beams, the ends having neither wall posts or braces. The nave is ceiled by a longitudinal ridge rib, supported at the apex of the cambered beams, and single intermediate longitudinal 'purlin' ribs to either side. All these further timbers are plain and unmoulded.

The aisles roofs to the north and south sides of the nave comprise four main 'tiebeams', cranked and moulded in a similar fashion to those of the nave roof, though of course much shorter (Fig 3b). Between the cranked tiebeams there are again a series of unmoulded intermediate beams, these intermediates, however, being straight rather than cranked, and acting as rafters, running 'lean-to' fashion from the wall plates of the aisles to a plate set above the arches of the nave. A plain longitudinal rib runs between the beams ceiling the aisle.

It was believed, on the basis of stylistic similarities and the overall structural integrity of the masonry, that the nave and both aisle roofs are of the same date, and could be associated with the early development of Apethorpe Hall in the late-fifteenth century. There is, however, no real evidence that St Leonard's is not a generation or so earlier than this, and that it may date to the early- to mid-fifteenth century . It is also possible that the aisles themselves could be of different dates to each other, although the masonry gives no indication of this.

The chancel roof

Whilst the roofs of the nave and aisles are similar throughout, that of the chancel shows greater variation, comprising three bays formed by three trusses (a possible further truss at the east end wall, truss '1', not extant). Two of these trusses, the 'middle' two, are of shallow pitched, king-post form with straight tiebeams, whilst the 'fourth' truss, at the chancel arch, is formed of a cranked tiebeam, similar, though with a shallower pitch, to those seen in the nave (Fig 4a/b). Between the trusses runs a ridge beam as well as, to each pitch of the roof, single, slightly staggered, purlins. All three tiebeams, the principal rafters, the ridge beam and purlins are given moulded decoration. The king posts are plain.

Each bay comprises four common rafters, the upper rafters, ie, those between purlin and ridge, always being slightly wider than the lower rafters, those between wall plate and purlin. Almost all these common rafters are plain, square-cut, and undecorated. The exception to this rule are those seen in bay three, where the upper four on the south side are all moulded in a style similar to that on the other decorated timbers of the chancel roof (Fig 5a).

It is clear, from the precision of the edges, the straightness of the timbers, and the regularity of the circular saw-marks, that some, probably twentieth or perhaps late-nineteenth century, repair and replacement has taken place within this roof; some sections of purlin, and several common rafters, are modern copies, the moulding, where necessary, being faithfully reproduced (Fig 5b). One or two of the older pieces have also had modern sections spliced into them.

The cranked tiebeam over the chancel arch also shows evidence for a possible still earlier phase of work to this roof. The end of the present ridge beam, for example, does not fit snugly into the mortice at the apex here, this being too large for the present timber and having a slightly different outline. There are also redundant mortices on this tiebeam where, it would appear, former purlins were housed, new mortices having been cut for the present purlins.

There is thus some evidence that timbers with different felling dates may be present in the chancel roof. The form of the chancel roof, however, with its king-post trusses, straight tiebeams, and purlins, is very similar, if not identical to that of the Mildmay Chapel, the timbers here having similar decorative mouldings. It is believed that this roof was constructed in AD 1621

SAMPLING

Sampling and analysis by tree-ring dating of timbers at Apethorpe church was requested by English Heritage. This was undertaken to support a programme of research being carried out at Apethorpe Hall by this body's Architectural Investigation Team, which will not only inform future repair and conservation decisions, but will also contribute towards several publications (Cattell *et al* forthcoming; Arnold and Howard 2008).

The sampling brief requested that the timbers in two areas in particular should be cored. Primarily these were the timbers of the north and south aisles, it being presumed that these were of the same date as those in the nave, the latter being currently inaccessible due to the height of this roof, the presence of fixed pews precluding the use of a mobile scaffold tower. The second area of sampling concerned the timbers of the chancel roof.

It was hoped that this programme of analysis would establish with greater certainty the date of both the north and south aisles, and by inference the date of the nave, and establish whether or not there is any difference in date between them. It was also hoped that tree-ring analysis would establish the date of the chancel roof, and whether it was earlier, the same, or a later date than that of the Mildmay Chapel, known to have been constructed in AD 1621.

Thus, from the material available, a total of 30 oak samples was obtained by coring, each sample being given the code APT-C (for Apethorpe, site 'C') and numbered 01–30. Of these 30 samples, seven, APT-C01–07, were taken from the cranked tiebeams of the north and south aisle. Whilst in theory other timbers were available here, particularly the straight intermediate rafters, all these, along with wall plates, wall beams, and longitudinal ribs, were derived from fast-grown trees; as such it was felt that they would be unlikely to provide samples with the minimum of 54 rings necessary for reliable tree-ring analysis. The remaining 23 samples, APT-C08–30, were obtained from the chancel roof, an attempt being made to sample a selection of different beam types and possible phases.

Where possible the positions of these samples are marked on plans and drawings made at the time of sampling, these being reproduced here as Figures 6a/b. Details of the samples are given in Table 1. In this Table all the trusses and other timbers have been numbered from east to west and further identified on a north–south basis as appropriate.

ANALYSIS

Each of the 30 samples obtained was prepared by sanding and polishing. It was seen at this point that six samples, APT-C04, C05, C15, C21, C22, and C26, had less than 54 rings, the minimum required for reliable dating, and so these were rejected from this programme of analysis. The annual growth rings of the remaining 24 samples were, however, measured, the data of these measurements being given at the end of this report. The data of these 24 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing three separate groups of cross-matching sample to be formed.

The first group comprises six samples, four from the cranked tiebeams of the north and south aisles, and two from the chancel roof, both of them representing king-posts. The samples of this group, shown in the bar diagram Figure 7, were combined at the offsets indicated to form site chronology APTCSQ01, with an overall length of 193 rings. Site chronology APTCSQ01 was then compared with an extensive corpus of reference chronologies, cross-matching consistently with a number of these when the date of its first ring is AD 1211 and the date of its last ring is AD 1403. The evidence of this cross-matching is given in the *t*-values of Table 2.

The second group comprises seven samples, all from the chancel roof, and includes all four moulded upper common rafters to the south side of bay 3 and the cranked tiebeam of truss 4; the other two samples are plain common rafters. The samples of this group, shown in the bar diagram Figure 8, were combined at the offsets indicated to form site chronology APTCSQ02, with an overall length of 139 rings. Site chronology APTCSQ02 was also compared with the reference chronologies, cross-matching consistently with a number of these when the date of its first ring is AD 1458 and the date of its last ring is AD 1596. The evidence of this cross-matching is given in the *t*-values of Table 3.

The third and final group to form comprises six samples, all of them again from the chancel roof. This group includes the principal rafters of the two king-post trusses, all such timbers being moulded, a moulded ridge beam, and one plain common rafter. The samples of this third group, shown in the bar diagram Figure 9, were combined at the offsets indicated to form site chronology APTCSQ03, with an overall length of 87 rings. Site chronology APTCSQ03 was also compared with the reference chronologies, cross-matching consistently with a number of these when the date of its first ring is AD 1579 and the date of its last ring is AD 1665. The evidence of this cross-matching is given in the *t*-values of Table 4.

Each of the three site chronologies was then compared with the remaining four measured but ungrouped samples. There was, however, no further satisfactory cross-matching. Each of the four remaining ungrouped samples was then compared individually with the reference chronologies, this indicating a cross-match for sample APT-C14 only, when the date of its first ring is AD 1659 and the date of its last ring is AD 1722. The evidence of this cross-matching is given in the *t*-values of Table 5.

This analysis can be summarised as below:

Site chronology	Number of samples	Number of rings	Date span (where dated)
APTCSQ01	6	193	AD 1211–1403
APTCSQ02	7	139	AD 1458–1596
APTCSQ03	6	87	AD 1579–1665
APT-C14	1	64	AD 1659–1722
	4	---	undated
	6	---	unmeasured

INTERPRETATION

Site chronology APTCSQ01 – the north and south aisle roofs and the chancel roof

None of the samples obtained from any of these timbers retains complete sapwood and it is thus not possible to indicate the precise felling date of any of the timbers represented. Several of them, however, do retain the heartwood/sapwood boundary. This means that only the sapwood element of the trees is missing, and it is thus possible to calculate an estimated felling date range for some of them.

Five of the six samples in site chronology APTCSQ01, representing timbers from the north and south aisles but also including two timbers from the chancel roof, retain the heartwood/sapwood boundary.

The position of the heartwood/sapwood boundary on these five samples varies by only 12 years, from relative position 181 (AD 1391) on sample APT-C02 to relative position 193 (AD 1403) on sample APT-C18. Given that such a limited variation is usually indicative of single-phase timbers, it is likely that the timbers represented were felled at the same time. The average date of this on these five samples is AD 1397. Using the usual 95% confidence limit of 15–40 rings for the amount of sapwood the trees might have had, would give the timbers represented an estimated felling date in the range AD 1412–37.

It is not possible to be certain of the felling date of the timber represented by the single remaining sample, APT-C09 in site chronology APTCSQ01, as it does not retain the heartwood/sapwood boundary. However, given the degree of cross-matching between APT-C09 and the other samples, with a value of t=12.9 with sample C18 and t=11.2 with samples C03, there is no reason to suspect that it is not of the same date.

Importantly in this respect, there is a high degree of cross-matching between sample APT-C03 from the north aisle roof and sample APT-C06 from the south aisle roof, with t=11.9. Such a level would indicate that the timbers represented are derived from two trees that were growing very close to each other, or indeed, derived from the same tree. If this is indeed the case it would support the view that the north and south aisles are of the same date as each other, the probability of two samples cross-matching with each other so highly being much less likely if the timbers were felled at different times.

Site chronology APTCSQ02 – chancel roof cranked tiebeam and moulded common rafters

The seven dated samples of site chronology APTCSQ02 represent the cranked tiebeam of the chancel roof along with the four moulded common rafters in bay 3 of the south slope, plus two plain common rafters. Only the sample representing the tiebeam retains the heartwood/sapwood boundary, this boundary being dated to AD 1596. Using the same 95% confidence limit of 15–40 rings for the amount of sapwood the tree might have had, would give the timber represented an estimated felling date in the range AD 1611–36.

The felling date range of the timbers represented by the other six samples in this group cannot be estimated because they do not have the heartwood/sapwood boundary. However, given the high degree of cross-matching seen between some of these samples, with values in excess of t=8.0, t=9.0, and even t=10.0 being seen, suggesting that the trees used are all from the same source, and indeed, the possibility that some beams are derived from the same tree, it is likely that all these timbers were felled at the same time.

Site chronology APTCSQ03 – chancel roof principal timbers

Of the six samples of site chronology APTCSQ03, four represent the principal rafters of the king post trusses, one represents a ridge beam, and the sixth a common rafter. All six samples retain the heartwood/sapwood boundary, the average date of this being AD 1660. Using the same 95% confidence for the amount of sapwood as above, would give the timbers represented an estimated felling date in the range AD 1675–1700. Given the similar position of the heartwood/sapwood boundaries on these samples, there is no reason to suspect that the timbers they represent were not all felled at the same time, a supposition supported by the fact that, with values in excess of t=11.0, t=12.0, and even t=14.0 being seen, it is likely that some timbers are derived from the same tree.

Sample APT-C14

A final timber is represented by the individually dated sample, APT-C14, a plain upper common rafter to the south side of bay 2. Having a heartwood/sapwood boundary date of AD 1722, and allowing for 15–40 sapwood rings, would give the timber represented an estimated felling date in the range AD 1737–62.

CONCLUSION

It would appear, therefore, that four phases of felling are have been detected amongst the sampled timbers of Apethorpe church. The earliest is that represented by site chronology APTCSQ01, comprised mainly of samples from the north and south aisles, plus the two king-posts, both presumably reused, in the chancel roof. These timbers have an estimated felling date in the range AD 1412–37.

A second phase of felling is represented by site chronology APTCSQ02, comprised of samples from timbers of the chancel, notably the cranked tiebeam at the chancel arch and the four moulded common rafters in bay 3 of the south slope of the roof. These timbers have a felling date in the range AD 1611–36. Such a date would suggest the possibility that the chancel was at least partly reroofed with cranked tiebeam trusses in the early seventeenth century, of which only one truss, that over the chancel arch, now remains. The construction of the adjoining Mildmay Chapel in 1621, which required the south wall of the chancel to be rebuilt, could have prompted the reroofing.

This early-seventeenth century roof appears to have been largely replaced in the late-seventeenth century by the present roof, comprising the two king-post trusses with straight tiebeams, and represented by the samples of site chronology APTCSQ03. These timbers (the principal rafters of these two trusses, and the ridge beam between them) have an estimated felling date in the range AD 1675–1700. A substantial rebuild of the chancel roof in the late-seventeenth century may imply that the early seventeenth-century roof retained a significant amount of medieval fabric, which needed replacing by the end of the century, with at least one medieval timber reused to provide king-posts for the new trusses.

Although the estimated felling date of the cranked tiebeam, AD 1611–36, brackets the date, AD 1621, of the Mildmay Chapel, the form of the chapel roof trusses is similar to that of the king-post trusses in the chancel roof, which are dated to AD 1675–1700. This might suggest that the present chapel roof is also later than AD 1621, but the late-seventeenth century chancel trusses may simply copy the basic form of the king-post trusses in the Mildmay Chapel; the mouldings on these trusses are not identical.

Be that as it may, a final phase of felling appears to be represented by the dating of the individual sample APT-C14. This timber, a plain common rafter, has an estimated felling date range of AD 1737–62. It is possible that it represents a phase of minor repair to the roof.

As intimated above, a number of samples probably represent timbers that were at least growing very close to each other in the same copse or stand of woodland, or, indeed, may represent timbers derived from the same tree. The timbers represented by samples APT-C03, C09, and C18 (a timber in the north aisle and the king posts of the chancel), in site chronology APTCSQ01, for example, cross-match with each other, with values in excess of t=11.0 and t=12.0. Samples APT-C24, C25, C27, and C29, all moulded common rafters, in site chronology APTCSQ02, also cross-match well, values in excess of t=9.0 and 10.0 being seen. The best matches, however, are seen between samples in site chronology APTCSQ03, where values approaching t=15.0 are seen, strongly suggesting timbers derived from the same tree.

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TABLES

Table 1: Details of tree-ring samples from St Leonard's Church, Apethorpe, Northamptonshire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date	Last heartwood ring date	Last measured ring date
	North aisle					
APT-C01	Truss 5, tiebeam	164	h/s	AD 1231	AD 1394	AD 1394
APT-C02	Truss 6, tiebeam	181	h/s	AD 1211	AD 1391	AD 1391
APT-C03	Truss 8, tiebeam	174	h/s	AD 1223	AD 1396	AD 1396
	South aisle					
APT-C04	Truss 5, tiebeam	nm	---	------	------	------
APT-C05	Truss 6, tiebeam	nm	---	------	------	------
APT-C06	Truss 7, tiebeam	138	h/s	AD 1264	AD 1401	AD 1401
APT-C07	Truss 8, tiebeam	55	no h/s	------	------	------
	Chancel roof					
APT-C08	Truss 2, tiebeam	54	no h/s	------	------	------
APT-C09	Truss 2, king post	164	no h/s	AD 1217	------	AD 1380
APT-C10	Truss 2, north principal rafter	75	h/s	AD 1587	AD 1661	AD 1661
APT-C11	Truss 2, south principal rafter	78	h/s	AD 1587	AD 1664	AD 1664
APT-C12	Bay 2, ridge beam	80	h/s	AD 1586	AD 1665	AD 1665
APT-C13	Bay 2, south upper common rafter 1	55	h/s	------	------	------
APT-C14	Bay 2, south upper common rafter 2	64	h/s	AD 1659	AD 1722	AD 1722
APT-C15	Bay 2, south upper common rafter 3	nm	---	------	------	------
APT-C16	Bay 2, south upper common rafter 4	75	no h/s	AD 1501	------	AD 1575

Table 1: continued

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date	Last heartwood ring date	Last measured ring date
	Chancel roof continued					
APT-C17	Truss 3, tiebeam	73	2	------	------	------
APT-C18	Truss 3, king post	157	h/s	AD 1247	AD 1403	AD 1403
APT-C19	Truss 3, north principal rafter	60	h/s	AD 1598	AD 1657	AD 1657
APT-C20	Truss 3, south principal rafter	81	h/s	AD 1579	AD 1659	AD 1659
APT-C21	Bay 3, ridge beam	nm	---	------	------	------
APT-C22	Bay 3, south purlin	nm	---	------	------	------
APT-C23	Bay 3, north lower common rafter 1	60	h/s	AD 1597	AD 1656	AD 1656
APT-C24	Bay 3, south upper common rafter 1	63	no h/s	AD 1499	------	AD 1561
APT-C25	Bay 3, south upper common rafter 2	96	no h/s	AD 1460	------	AD 1555
APT-C26	Bay 3, north upper common rafter 3	nm	---	------	------	------
APT-C27	Bay 3, south upper common rafter 3	77	no h/s	AD 1458	------	AD 1534
APT-C28	Bay 3 north upper common rafter 4	73	no h/s	AD 1509	------	AD 1581
APT-C29	Bay 3, south upper common rafter 4	55	no h/s	AD 1480	------	AD 1534
APT-C30	Truss 4, tiebeam	95	h/s	AD 1502	AD 1596	AD 1596

*NM = not measured

**h/s = the heartwood/sapwood ring is the last ring on the sample

C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence APTCSQ01 and relevant reference chronologies when first ring date is AD 1211 and last ring date is AD 1403

Reference chronology	Span of chronology	*t*-value	
Brockworth Court (house and wing), Brockworth, Glos	AD 1281–1447	10.3	(Howard 2000)
Reading Waterfront, Berks	AD 1160–1407	9.4	(Groves *et al* 1997)
19 Henley Street, Alcester, Warwicks	AD 1322–1393	9.1	(Alcock *et al* 1989)
Ulverscroft Priory, Charnwood Forest, Leics	AD 1219–1463	8.8	(Arnold *et al* 2008)
East Midlands	AD 882–1981	8.4	(Laxton and Litton 1988)
Abbey Farm Barns, Thetford, Norfolk	AD 1237–1428	8.2	(Howard *et al* 2000)
England, London	AD 413–1728	7.9	(Tyers and Groves 1999 unpubl)
Chicksands Priory, Chicksands, Beds	AD 1200–1541	7.8	(Howard *et al* 1998)

Table 3: Results of the cross-matching of site sequence APTCSQ02 and relevant reference chronologies when first ring date is AD 1458 and last ring date is AD 1596

Reference chronology	Span of chronology	*t*-value	
East Midlands	AD 882–1981	9.2	(Laxton and Litton 1988)
Kingsbury Hall, Kingsbury, Warwicks	AD 1391– 564	9.2	(Arnold and Howard 2006)
Nevill Holt, Leicestershire	AD 1274–1534	8.8	(Howard 2001 unpubl)
Stoneleigh Abbey, Stoneleigh, Warwicks	AD 1398–1658	8.3	(Howard *et al* 2000)
England	AD 401–1981	7.9	(Baillie and Pilcher 1982 unpubl)
England, London	AD 413–1728	7.8	(Tyers and Groves 1999 unpubl)
Church of St Andrew, Welham, Leics	AD 1443–1633	7.7	(Arnold *et al* 2005)
Kenilworth Castle Gatehouse, Kenilworth, Warwicks	AD 1390–1547	7.0	(Arnold and Howard 2007)

Table 4: Results of the cross-matching of site sequence APTCSQ03 and relevant reference chronologies when first ring date is AD 1579 and last ring date is AD 1665

Reference chronology	Span of chronology	*t*-value	
Newington House, Oxon	AD 1540–1678	6.6	(Haddon-Reece 1987)
Worcester Cathedral	AD 1484–1772	6.2	(Arnold *et al* 2003)
Newdigate, Surrey	AD 1261–1639	5.5	(Bridge 1998)
The Old Hat Shop, Tewkesbury, Glos	AD 1484–1664	5.1	(Nayling 2000)
East Midlands	AD 882–1981	4.9	(Laxton and Litton 1988)
Stoneleigh Abbey, Stoneleigh, Warwicks	AD 1398–1658	4.9	(Howard *et al* 2000)
Bolsover Castle riding house, Bolsover, Derbys	AD 1494–1744	4.5	(Arnold *et al* 2005)
Southwell Minster (north chancel aisle roof), Southwell, Notts	AD 1573–1716	4.4	(Howard *et al* 1996)

Table 5: Results of the cross-matching of sample APT-C14 and relevant reference chronologies when first ring date is AD 1659 and last ring date is AD 1722

Reference chronology	Span of chronology	*t*-value	
Shenton dovecote, Shenton, Leics	AD 1606–1719	6.1	(Arnold *et al* 2008)
Old Abbey Farm, Risley, Cheshire	AD 1667–1753	6.1	(Nayling 1998)
Claydon House, Claydon, Bucks	AD 1613–1756	6.0	(Tyers 1995)
Mapledurham, New Farm barn, Oxon	AD 1658–1739	6.0	(Haddon-Reece 1987)
East Midlands	AD 882–1981	5.8	(Laxton and Litton 1988)
Worcester Cathedral	AD 1484–1772	5.8	(Arnold *et al* 2003)
Lathom House, Lancashire	AD 1633–1726	5.1	(Nayling 2000)
St John The Baptist, Knossington, Leics	AD 1662–1721	5.0	(Arnold *et al* 2005)

FIGURES

Figure 1: location of Apethorpe, Northamptonshire (circled)

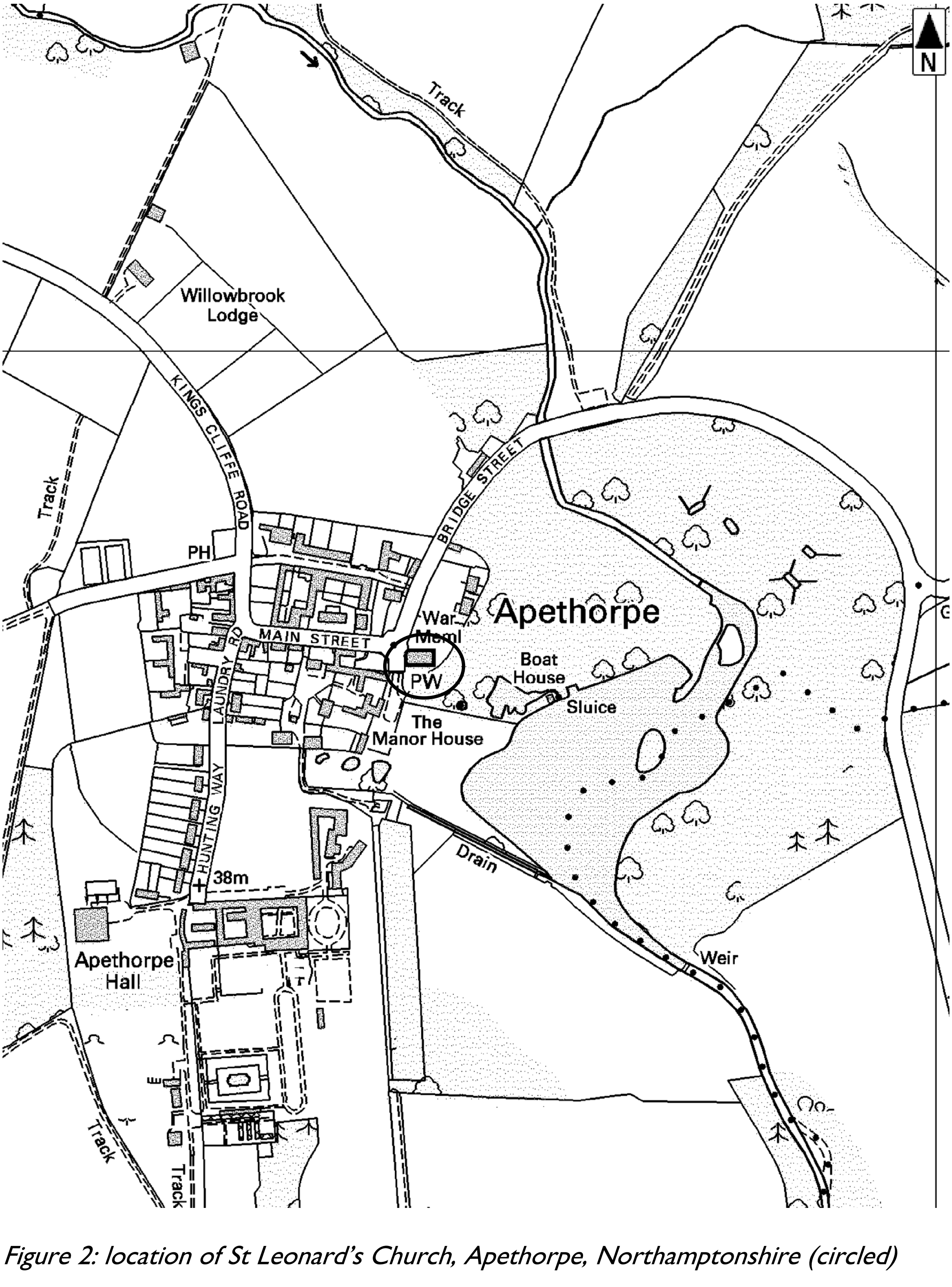


Figure 2: location of St Leonard's Church, Apethorpe, Northamptonshire (circled)

Figure 3a (top): View of the nave roof from the east end looking west

Figure 3b (bottom): View of the north aisle roof from the west looking east

Figure 4a (top): View of the chancel roof looking west to east showing the straight tiebeams of trusses 2 and 3

Figure 4b (bottom): View of the chancel roof looking east to west showing the cranked tiebeam of truss 4 at the chancel arch

Figure 5a (top): View of the moulded tiebeam of truss 3, the moulded upper south common rafters in bay 3 and the plain common rafters.

Figure 5b (bottom): Modern replacement purlin and lower common rafters

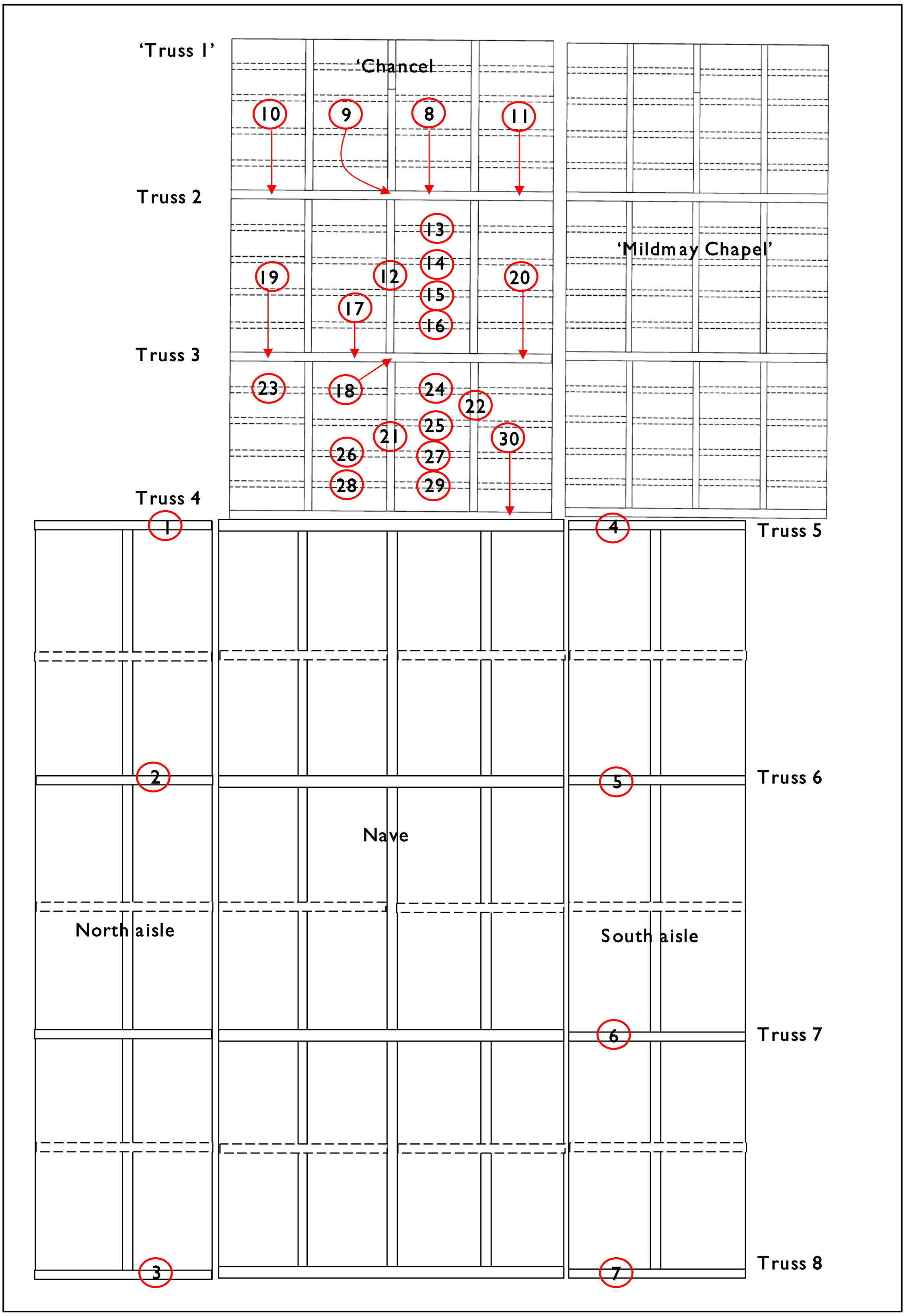


Figure 6a: Plan of St Leonard's Church to show position of sampled timbers

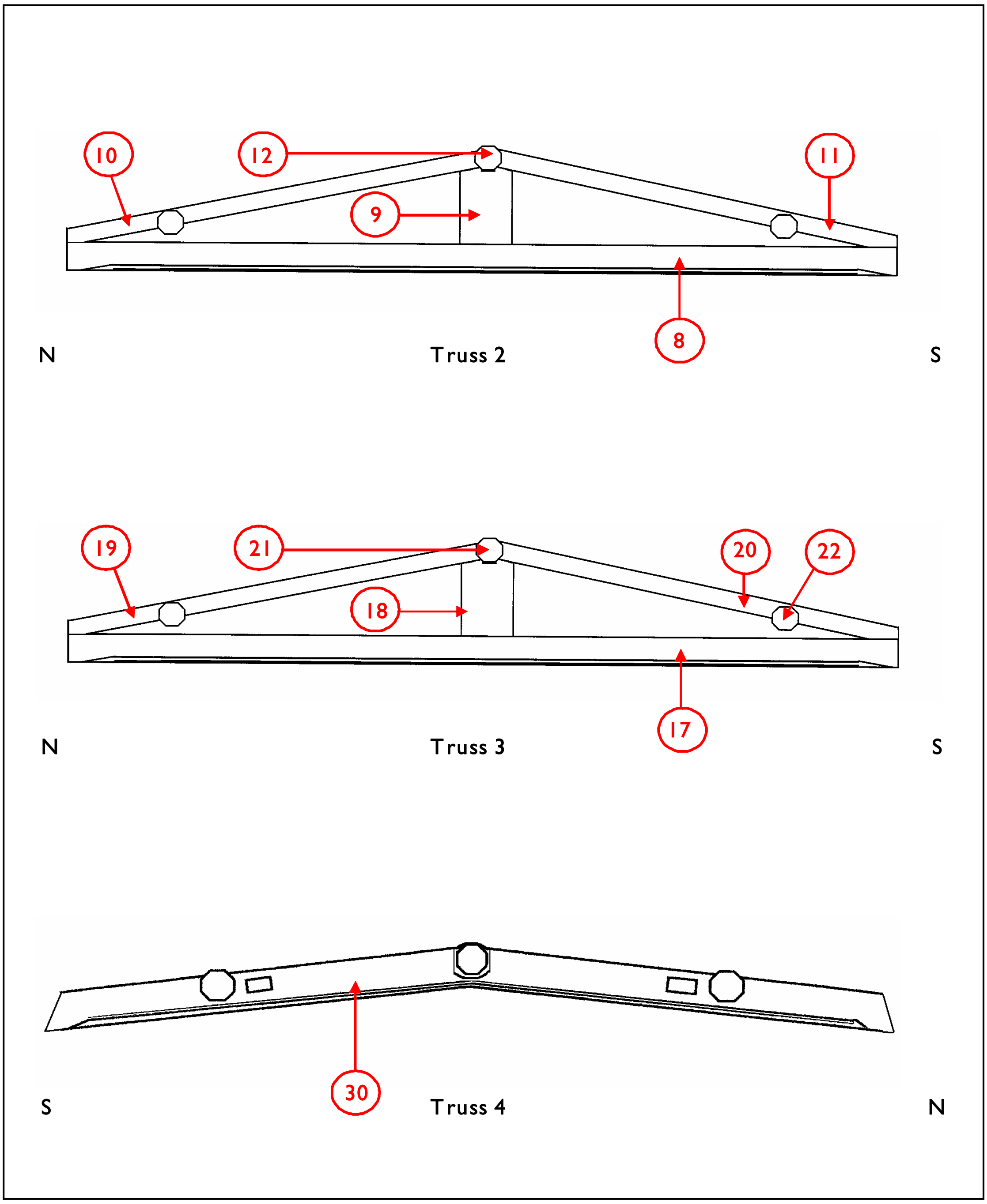
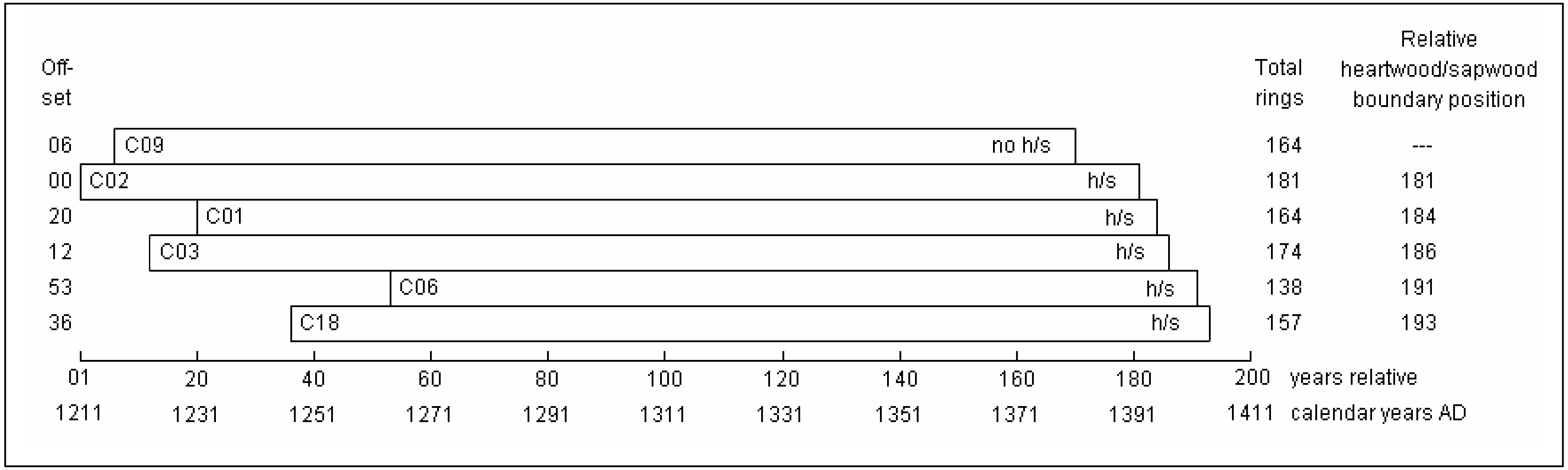


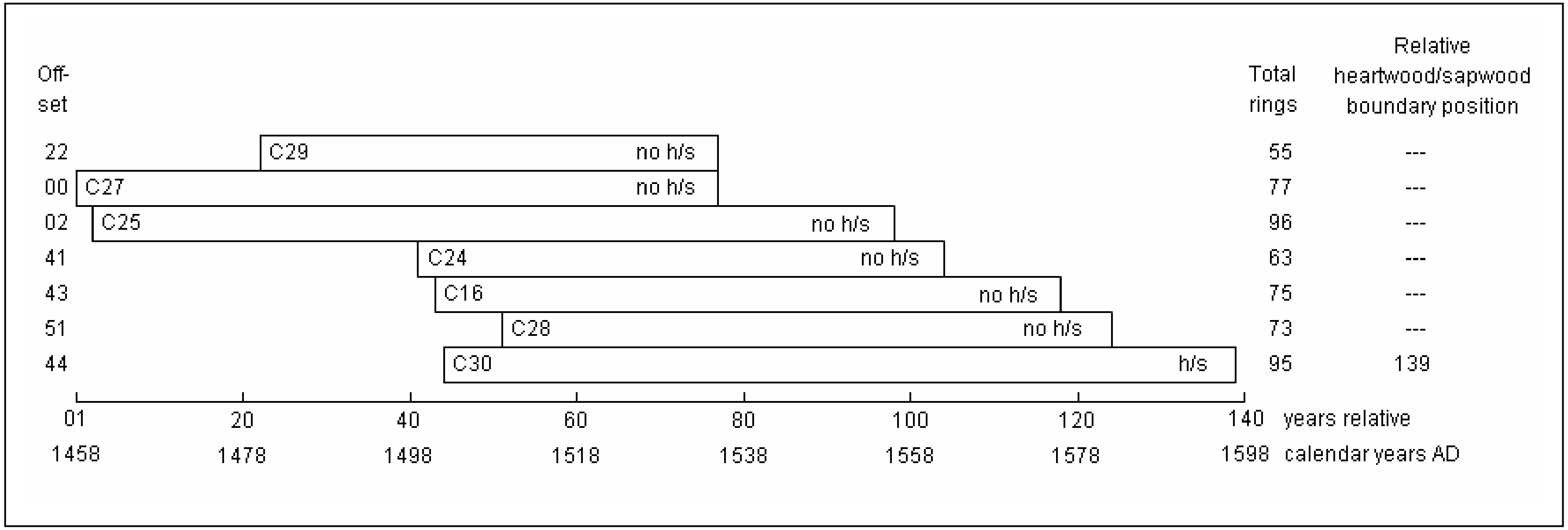
Figure 6b: Sketch sections of the chancel trusses to show sampled timbers

(viewed as noted in each drawing)



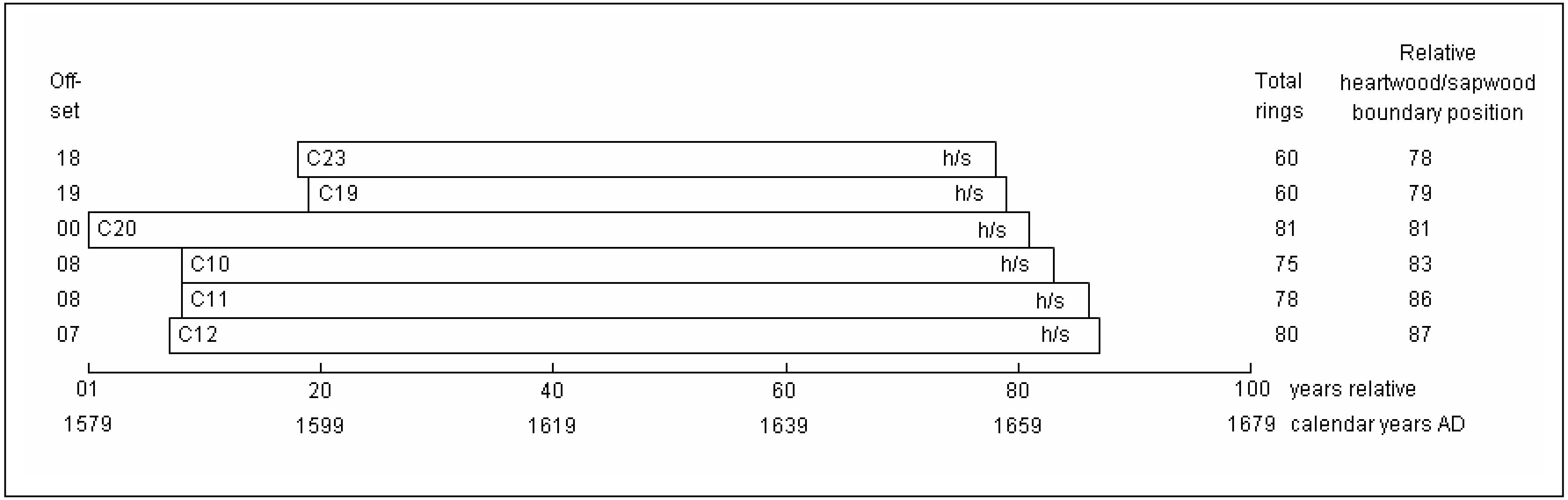
Empty bars [ ] = heartwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing

Figure 7: Bar diagram of samples in site chronology APTCSQ01



Empty bars [ ] = heartwood rings.
h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing

Figure 8: Bar diagram of samples in site chronology APTCSQ02



Empty bars ☐ = heartwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing

Figure 9: Bar diagram of samples in site chronology APTCSQ03

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

APT-C01A 164
234 94 177 160 176 179 347 168 272 194 141 135 203 143 166 164 177 139 204 183
153 134 215 208 333 156 350 184 231 216 160 173 113 115 124 119 78 127 79 81
98 116 111 109 106 82 84 80 46 68 69 66 63 67 91 77 71 177 318 172
79 155 152 137 129 105 92 99 88 138 76 81 64 36 33 49 37 47 34 47
31 34 36 30 26 24 34 21 34 34 35 45 34 28 32 26 37 30 35 41
20 24 28 37 46 31 30 36 48 33 29 23 33 44 36 43 42 35 34 45
67 39 37 52 30 31 52 27 38 50 33 39 76 58 48 46 46 49 60 52
52 58 47 81 47 46 72 82 92 69 75 88 68 45 66 54 72 75 58 56
52 67 82 81
APT-C01B 164
212 89 174 179 177 172 337 171 259 194 140 137 209 122 178 162 164 141 191 203
144 135 216 208 307 164 354 184 236 230 138 178 112 109 129 124 75 122 83 72
101 116 112 102 101 74 86 74 37 73 71 65 58 75 84 86 74 184 324 192
92 139 159 139 121 115 89 112 82 130 97 78 64 41 35 49 38 43 38 40
36 36 35 32 22 23 40 29 27 32 34 43 36 32 30 25 34 36 37 39
18 24 30 34 50 38 29 29 52 42 23 31 30 39 32 44 41 40 41 38
68 37 34 56 26 31 51 25 43 48 30 24 98 55 59 41 33 66 54 47
53 65 40 71 56 45 72 87 95 63 77 83 64 42 66 51 74 83 62 50
54 84 74 64
APT-C02A 181
482 299 407 275 413 393 302 247 244 183 204 250 37 46 45 64 94 61 72 43
53 77 119 100 188 148 223 222 313 363 308 328 230 187 229 176 200 232 226 185
176 156 310 303 393 245 279 158 196 251 280 440 316 323 243 190 159 152 227 186
212 242 276 197 240 152 151 121 139 135 293 217 253 343 298 243 225 188 338 281
491 389 335 238 319 248 271 248 231 252 236 233 161 147 197 249 355 304 242 196
223 192 167 95 136 181 144 113 189 145 188 113 117 105 85 121 214 164 187 239
140 193 182 156 245 145 245 245 319 271 217 145 213 167 163 176 189 195 150 94
133 84 233 286 255 162 206 166 205 161 171 353 274 253 161 96 81 88 127 116
97 166 101 193 156 197 232 215 210 275 283 260 249 160 171 154 248 170 132 112
153
APT-C02B 181
519 308 407 277 390 368 308 250 234 179 174 220 52 48 55 50 94 62 69 47
60 89 127 100 211 157 206 233 308 358 304 333 224 187 226 179 202 222 233 194
166 159 299 302 400 222 281 158 182 267 281 417 314 328 243 201 176 143 206 189
232 235 275 178 216 157 136 113 109 146 290 218 244 350 288 247 222 187 342 284
477 396 332 238 313 242 258 244 215 260 257 242 157 150 193 234 353 292 256 198
220 180 157 104 140 166 146 120 204 137 178 132 111 111 94 107 247 160 173 248
136 178 205 158 242 145 263 240 327 271 225 154 213 163 174 170 185 181 152 94
137 100 237 282 254 166 213 159 210 156 163 362 268 261 148 94 79 82 121 122
97 159 100 199 153 193 230 204 215 298 284 279 227 149 167 160 252 164 135 128
155
APT-C03A 174
236 322 255 273 131 183 247 241 179 116 177 165 197 192 272 225 356 244 166 136
243 196 254 205 205 172 181 274 299 265 377 299 415 279 230 142 226 372 369 507
260 246 266 179 97 124 173 189 225 160 144 125 136 155 249 214 174 147 194 185
233 150 151 172 77 92 169 160 212 247 362 306 252 170 162 165 118 181 202 193
116 96 83 99 104 123 171 193 137 168 122 161 153 64 51 58 70 89 133 159

156 142 118 85 135 127 119 166 112 99 95 125 160 142 150 151 188 179 124 128
130 112 126 145 140 137 96 76 94 93 140 125 60 71 83 69 75 90 61 91
88 111 73 68 57 84 140 96 94 132 58 90 68 58 79 118 104 104 96 77
103 87 75 105 137 115 93 74 57 79 78 84 81 113
APT-C03B 174
200 322 260 266 126 189 251 240 193 111 184 176 197 172 275 235 338 239 159 142
234 198 244 205 220 156 183 261 276 262 361 307 419 273 198 158 232 376 355 494
256 265 255 184 97 125 165 184 229 163 160 152 138 163 248 200 183 137 204 192
225 164 159 148 93 80 168 168 215 260 356 321 239 156 138 160 139 174 197 205
113 108 70 116 95 127 157 206 145 146 124 156 132 79 54 63 71 84 128 152
166 148 117 72 140 132 121 173 104 106 93 119 179 134 140 151 196 169 133 133
117 112 128 136 142 145 94 70 90 90 148 117 61 69 92 70 75 88 70 70
111 96 77 57 65 84 133 124 81 143 70 88 68 56 85 132 107 102 103 73
103 73 80 112 126 118 85 76 70 57 79 96 97 93
APT-C06A 138
299 306 219 126 162 195 181 241 209 286 208 215 206 333 296 309 302 372 301 335
217 220 238 125 176 271 228 258 314 393 419 331 288 316 245 161 182 187 210 139
120 78 112 154 123 132 156 126 144 118 101 107 141 142 119 120 137 197 166 175
154 136 97 167 128 131 172 116 92 106 117 169 128 147 157 205 150 124 138 120
122 146 166 141 144 100 80 136 121 206 144 85 92 140 78 101 119 70 72 107
101 71 66 86 89 133 117 108 125 88 95 88 76 106 163 126 114 113 101 138
102 111 136 163 161 121 116 137 70 156 140 138 142 72 92 90 70 76
APT-C06B 138
302 306 220 119 169 189 195 228 211 283 220 219 209 330 283 332 324 322 294 358
209 247 248 138 172 283 260 236 306 388 423 355 295 305 241 179 174 183 208 128
122 88 117 146 130 126 144 127 147 120 111 107 138 146 127 115 143 187 159 186
151 127 107 158 134 130 177 118 89 100 120 162 130 146 153 195 151 132 140 125
114 149 164 145 136 109 80 130 123 208 145 86 78 125 97 109 105 72 70 100
108 73 63 84 91 133 126 90 131 91 101 93 75 91 162 122 109 113 110 133
90 129 136 149 178 115 135 132 79 144 131 122 147 78 94 102 74 81
APT-C07A 55
188 169 200 265 226 234 267 271 224 266 200 252 152 294 156 203 198 280 203 221
227 172 203 164 194 204 188 169 135 133 124 152 149 137 108 136 108 159 145 82
117 136 158 205 173 249 193 142 107 200 212 214 169 191 138
APT-C07B 55
197 209 192 232 224 258 285 183 226 279 193 242 149 291 158 192 215 286 212 218
243 173 201 168 188 204 201 177 122 120 112 166 136 145 108 133 108 179 132 76
114 136 134 207 171 246 200 152 108 189 215 286 159 194 136
APT-C08A 54
360 295 200 221 233 196 239 236 258 313 209 132 139 223 192 315 266 270 257 264
195 243 208 195 246 239 267 95 113 65 94 80 94 105 136 104 140 136 130 94
133 143 130 148 109 155 148 180 199 134 244 226 150 187
APT-C08B 54
332 295 208 230 229 193 235 234 260 314 212 132 138 213 180 316 280 281 225 262
201 238 208 197 246 243 279 87 104 71 90 74 86 118 136 104 149 136 132 87
131 140 144 162 105 155 159 183 184 139 255 223 136 170
APT-C09A 164
264 192 297 257 192 211 213 181 170 182 110 143 184 147 148 136 170 179 184 152
265 191 180 155 111 81 128 109 144 105 95 88 110 154 145 142 193 197 282 151
146 72 70 144 144 168 88 110 135 89 58 69 53 93 107 84 90 69 84 82
126 157 71 70 70 61 77 61 75 67 62 66 117 141 141 169 199 115 124 65
83 62 48 61 98 121 63 69 82 95 82 119 92 90 82 58 66 104 120 75
84 81 76 100 117 123 114 110 87 97 117 101 84 90 64 64 90 95 96 78

53 101 116 92 71 67 92 60 70 72 89 75 48 53 83 65 82 88 50 50
61 56 52 63 57 82 92 72 54 59 53 50 75 64 72 79 54 69 57 50
56 58 74 74
APT-C09B 164
231 199 272 265 181 216 222 187 160 180 127 155 180 149 138 130 168 170 193 172
247 158 213 154 115 79 140 113 144 120 88 85 132 152 160 144 205 191 277 155
156 87 57 150 143 159 95 113 146 72 59 62 62 83 98 74 99 58 93 80
128 163 68 77 67 56 82 59 73 62 73 74 112 140 146 165 199 115 106 72
78 63 52 62 101 110 67 71 75 98 85 122 91 86 85 58 60 109 127 75
81 75 80 96 116 125 112 110 88 74 115 103 77 92 63 66 89 85 99 80
56 101 119 94 72 71 81 64 71 70 88 71 58 53 83 63 78 98 48 49
60 58 57 54 59 78 94 79 59 59 43 55 68 70 69 88 65 73 56 48
55 62 73 61
APT-C10A 75
495 557 500 260 310 299 385 390 347 338 281 232 270 303 250 251 218 214 162 223
200 208 182 183 117 156 97 105 113 140 164 131 89 189 171 126 135 132 252 235
251 230 222 201 170 317 154 241 153 131 183 291 238 196 207 156 153 136 149 178
115 173 126 91 124 64 62 70 223 126 87 144 130 122 139
APT-C10B 75
664 518 482 268 289 300 383 460 340 329 270 238 282 282 225 251 241 237 176 235
226 205 206 158 133 141 100 103 104 143 159 145 84 182 189 132 121 127 223 205
243 231 220 201 169 322 152 235 154 135 173 290 251 180 207 158 143 134 155 167
118 169 135 111 112 60 62 79 195 138 101 144 116 124 142
APT-C11A 78
322 373 498 301 309 338 415 466 426 359 290 263 242 301 177 249 271 323 241 277
257 317 241 233 175 172 172 149 204 242 293 239 123 303 257 190 227 137 244 225
278 228 208 156 136 211 121 176 110 103 155 177 140 137 154 123 121 119 126 136
107 149 130 126 179 94 83 89 188 107 95 144 91 99 108 114 135 133
APT-C11B 78
273 425 490 297 343 331 436 434 441 370 291 259 255 325 165 281 291 315 230 291
267 343 260 244 158 177 164 191 196 241 293 253 119 299 241 206 217 151 246 212
304 206 207 167 157 207 118 189 131 87 152 182 150 113 160 106 117 117 133 130
113 137 147 137 173 95 85 88 185 120 81 144 95 107 111 130 139 151
APT-C12A 80
375 373 174 219 128 147 159 227 274 247 210 162 203 196 178 157 134 140 133 136
168 150 204 167 187 116 120 200 167 168 217 211 180 128 372 255 209 183 101 122
121 142 139 142 130 126 197 129 155 159 120 130 202 185 161 193 161 159 170 186
204 142 197 132 147 167 119 99 130 254 174 120 203 158 153 135 169 222 221 235
APT-C12B 80
374 352 157 253 141 148 167 239 300 234 222 178 215 195 181 123 146 156 136 116
205 147 204 179 188 108 133 192 188 174 202 193 184 134 364 256 218 182 91 125
109 133 151 150 138 127 182 102 174 157 115 144 211 152 147 201 154 140 159 183
217 159 203 139 140 163 134 119 116 237 155 122 203 162 132 133 158 230 217 238
APT-C13A 55
338 341 338 201 172 173 255 211 269 315 274 201 198 222 356 349 243 361 260 214
235 230 334 242 310 250 393 502 327 289 309 484 489 327 275 365 410 248 304 225
246 237 294 281 192 331 399 506 480 313 331 247 264 342 244
APT-C13B 55
393 346 315 204 173 174 251 221 257 308 283 211 204 217 346 345 212 352 263 196
223 236 318 278 326 242 440 484 356 288 316 468 514 354 263 383 404 251 272 245
243 252 302 279 184 347 392 509 480 305 349 231 290 342 243
APT-C14A 64
134 228 166 202 202 201 231 159 174 212 174 167 261 161 199 181 248 380 524 435

580 439 209 401 363 246 149 369 226 172 138 110 112 185 174 177 175 194 293 266
106 168 204 142 172 170 114 196 210 285 285 182 176 167 239 166 185 209 211 176
137 173 207 214
APT-C14B 64
112 212 168 204 203 208 239 161 180 204 186 156 252 167 211 179 244 394 539 399
584 434 230 412 370 253 145 359 229 191 131 113 129 187 151 190 175 202 253 290
107 161 216 129 178 159 113 195 204 296 293 180 163 200 225 152 176 205 201 159
144 171 202 212
APT-C16A 75
350 526 460 315 206 211 213 198 249 246 358 513 409 225 132 146 127 211 156 103
108 157 113 157 127 135 163 174 148 137 199 174 170 210 230 199 176 203 181 182
163 89 149 94 141 119 97 103 127 142 132 152 149 143 146 112 89 152 226 209
143 196 294 242 225 235 269 219 185 234 130 161 211 141 156
APT-C16B 75
340 522 432 345 280 237 224 193 255 234 490 474 412 220 134 157 135 210 157 111
107 148 123 162 125 124 163 177 132 151 223 166 187 207 202 209 178 162 193 180
152 94 142 114 133 130 93 110 120 147 142 155 151 141 153 95 107 148 209 215
154 194 308 236 220 249 265 213 165 254 159 153 199 140 151
APT-C17A 73
460 382 597 588 621 447 284 202 209 226 271 289 327 268 254 208 173 216 135 210
207 226 162 222 188 281 147 200 238 178 272 189 195 181 162 267 198 292 261 169
141 134 168 104 205 163 75 89 104 128 68 117 142 67 77 95 98 100 79 68
47 86 119 135 117 177 115 151 101 100 75 85 124
APT-C17B 73
433 379 535 562 630 455 273 202 216 229 267 276 297 250 255 197 167 232 126 203
196 189 185 259 197 291 163 189 226 194 259 201 185 170 178 247 169 292 262 171
138 143 161 107 196 167 84 95 94 122 88 112 131 84 73 92 102 101 68 54
58 93 130 143 105 190 119 162 105 98 90 108 118
APT-C18A 157
85 92 136 184 172 152 220 207 284 178 196 98 109 166 177 252 173 195 217 170
84 77 72 63 76 76 96 58 115 96 137 181 104 92 99 105 139 147 113 79
68 62 146 180 266 237 285 223 203 133 98 104 78 86 142 163 108 146 174 189
216 301 250 210 170 149 130 160 241 134 102 104 137 145 158 146 109 125 103 94
193 202 165 194 102 109 135 165 280 182 150 160 203 188 102 140 124 100 111 190
159 192 136 89 139 132 190 175 86 69 117 97 114 90 65 126 158 148 139 98
88 92 164 166 135 179 93 113 77 95 112 138 151 149 176 174 172 91 114 150
206 169 103 91 100 95 133 122 100 118 112 114 87 103 115 80 164
APT-C18B 157
90 100 135 170 174 150 222 211 287 185 197 101 108 154 181 263 160 198 199 186
83 82 58 77 78 79 82 60 105 107 140 181 106 103 95 93 132 152 111 91
77 73 121 173 217 252 277 232 210 131 103 107 74 82 145 157 115 141 173 190
225 296 261 201 164 141 136 161 236 136 105 102 146 143 153 141 116 134 98 93
184 192 169 198 100 98 124 149 273 161 143 163 193 191 119 137 122 88 111 194
171 190 127 102 142 120 191 187 90 66 113 99 89 81 87 114 152 135 118 121
76 102 168 166 137 182 84 105 78 97 118 125 160 145 171 174 170 104 105 150
205 169 116 100 84 95 130 127 101 133 122 120 84 104 98 77 155
APT-C19A 60
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210 115 244 258 228 133 128 232 163 202 240 237 197 139 234 135 195 248 146 205
424 221 159 184 115 89 87 88 88 88 122 92 56 115 61 62 58 190 118 89
APT-C19B 60
366 431 378 398 435 460 353 257 369 309 269 289 233 212 150 130 151 182 160 243
192 108 240 240 230 137 130 188 173 201 234 231 210 131 227 139 195 260 158 207

412 270 190 197 128 108 94 116 125 102 125 102 81 106 46 53 59 193 117 86
APT-C20A 81
314 366 227 227 236 200 319 275 428 339 261 143 169 234 242 319 278 315 268 248
245 273 198 207 235 234 185 269 214 228 201 172 140 130 110 114 115 139 134 147
83 328 168 126 129 112 158 153 170 165 124 93 90 115 67 109 104 69 78 118
88 74 109 90 71 76 105 98 92 117 82 77 96 76 62 60 156 102 79 96
95
APT-C20B 81
265 366 206 206 267 184 288 270 468 335 243 139 182 223 253 331 259 326 243 236
244 273 194 209 215 250 183 269 198 228 215 172 134 132 116 108 105 138 137 133
88 330 172 124 131 111 156 153 172 162 110 102 83 113 77 104 95 78 83 121
82 83 98 83 85 84 91 102 89 120 74 76 96 84 63 57 171 95 80 94
93
APT-C23A 60
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424 415 265 451 479 337 462 407 521 478 404 348 339 263 367 354 354 269 296 183
193 252 292 236 254 196 204 212 223 329 262 307 256 245 200 148 116 94 194 222
APT-C23B 60
270 230 280 292 255 250 221 217 220 403 381 371 424 485 453 443 528 343 304 378
404 421 271 448 453 301 439 418 508 448 405 328 351 264 378 389 363 267 291 175
189 271 291 240 249 206 200 211 210 357 247 307 298 222 194 166 102 94 190 243
APT-C24A 63
189 163 172 153 169 173 172 168 120 134 186 154 155 164 132 107 96 81 88 146
118 90 73 113 64 74 34 49 109 76 66 46 88 60 92 161 232 192 153 139
157 116 128 133 145 63 76 78 91 126 143 136 90 94 113 137 112 67 69 64
117 83 92
APT-C24B 63
187 168 164 142 159 194 162 174 137 146 170 157 147 154 126 101 95 79 81 128
136 89 53 118 72 66 43 54 101 85 65 50 80 58 89 171 232 191 151 126
158 127 125 135 141 66 99 92 110 161 142 122 97 89 113 128 107 75 54 80
119 77 87
APT-C25A 96
263 160 170 159 118 175 150 172 218 231 244 205 277 197 253 256 224 262 240 312
282 413 325 241 208 152 135 186 157 182 219 185 139 163 202 190 273 139 147 177
157 154 177 167 194 203 201 161 168 180 190 128 171 138 95 101 133 123 175 196
127 96 140 87 101 80 73 116 103 112 86 113 79 120 172 221 195 102 147 187
156 153 145 159 99 144 140 116 160 164 156 168 120 151 177 159
APT-C25B 96
238 157 171 154 113 172 148 170 227 239 209 215 273 209 249 262 210 256 224 298
278 417 329 247 204 147 133 175 164 168 217 185 139 179 202 194 279 139 147 172
168 160 173 158 208 195 211 161 176 175 179 135 176 123 105 91 124 120 185 201
129 91 132 96 100 70 79 113 108 112 69 124 83 108 192 194 193 112 154 175
149 163 147 184 91 144 127 128 148 158 143 171 119 160 163 154
APT-C27A 77
126 131 132 138 141 176 156 164 179 252 316 302 240 238 333 245 319 454 300 298
236 357 280 420 394 319 250 187 269 404 321 403 388 313 234 265 266 235 280 147
162 200 198 189 161 146 178 163 173 124 129 129 140 107 123 116 95 69 73 100
189 141 85 75 128 60 83 43 60 99 79 70 54 106 84 206 299
APT-C27B 77
125 140 125 141 144 155 191 155 186 256 311 313 233 234 325 254 307 404 300 271
244 347 278 433 428 311 243 187 255 372 296 370 412 361 231 263 257 240 275 155
171 208 201 178 174 149 181 156 169 140 126 143 130 110 121 107 89 72 73 99
181 136 85 67 138 61 83 36 55 87 89 74 59 98 82 199 303

APT-C28A 73
318 354 372 449 428 349 325 278 233 426 506 380 230 320 255 271 217 214 278 300
236 181 240 254 195 255 299 214 185 210 203 137 162 117 165 145 180 130 108 146
160 144 128 140 158 178 183 128 117 185 216 200 197 199 224 143 112 137 163 171
153 207 158 158 153 105 103 97 100 113 139 208 116
APT-C28B 73
215 344 374 453 405 357 332 270 245 428 500 382 245 302 249 287 212 219 277 283
238 175 242 255 203 272 290 215 185 207 185 152 151 121 170 146 170 139 114 139
160 136 142 140 145 179 197 122 120 164 216 202 181 196 224 137 115 134 166 182
164 197 169 161 143 109 92 105 95 114 144 197 116
APT-C29A 55
278 415 374 151 192 157 157 280 189 181 269 210 176 224 211 196 262 198 180 195
209 202 213 174 263 228 278 228 210 213 251 147 218 184 127 125 158 154 223 236
116 111 141 85 87 77 86 118 132 126 64 100 89 203 279
APT-C29B 55
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217 204 216 185 249 217 258 221 238 239 230 161 225 195 136 135 156 132 206 188
122 94 153 99 79 62 61 153 103 124 69 100 89 200 279
APT-C30A 95
446 533 434 461 360 350 367 373 400 653 738 666 433 494 329 269 426 498 353 233
276 208 221 145 208 271 265 217 195 232 165 194 186 315 265 264 236 235 202 262
226 254 223 228 154 100 180 242 155 192 111 153 161 172 132 129 135 163 162 142
161 130 127 101 101 104 110 102 101 120 84 95 71 58 67 88 83 98 124 101
74 139 146 353 414 305 182 244 171 199 214 287 395 313 367
APT-C30B 95
491 521 450 443 372 348 357 361 394 625 774 691 426 462 352 248 435 506 358 244
269 201 225 140 233 250 264 212 195 230 174 185 179 298 249 267 239 236 202 266
221 243 232 227 143 109 174 240 161 197 100 168 152 175 134 117 139 169 148 141
165 125 117 108 100 99 111 103 101 95 93 101 62 53 70 99 79 104 116 97
86 132 147 371 387 311 162 244 184 188 238 281 380 322 374

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 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in 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

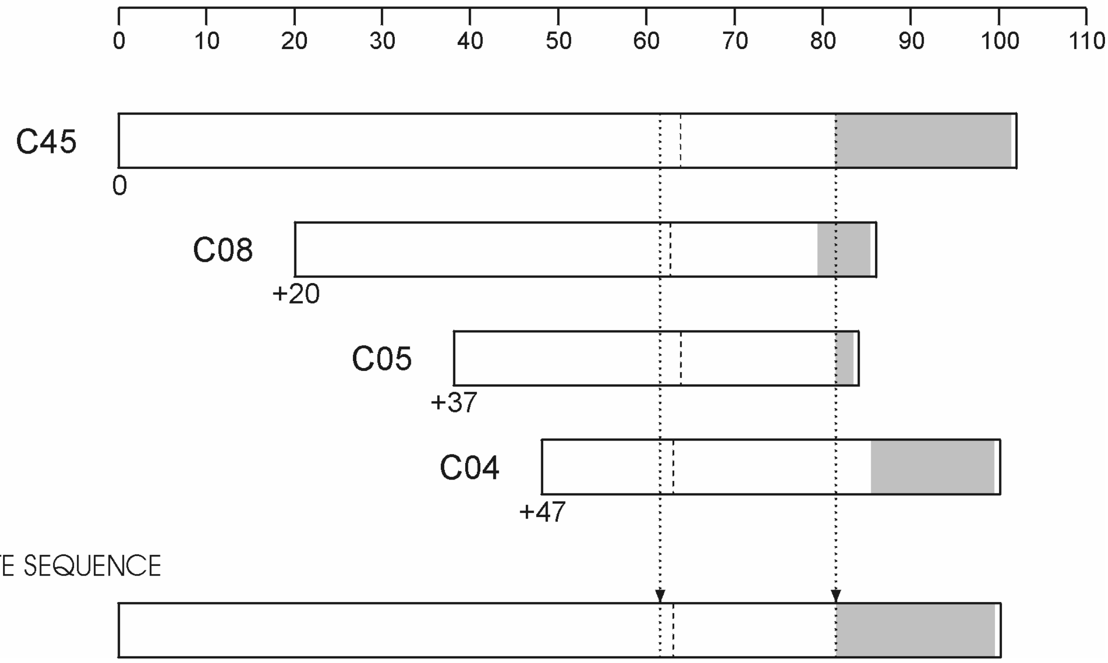


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

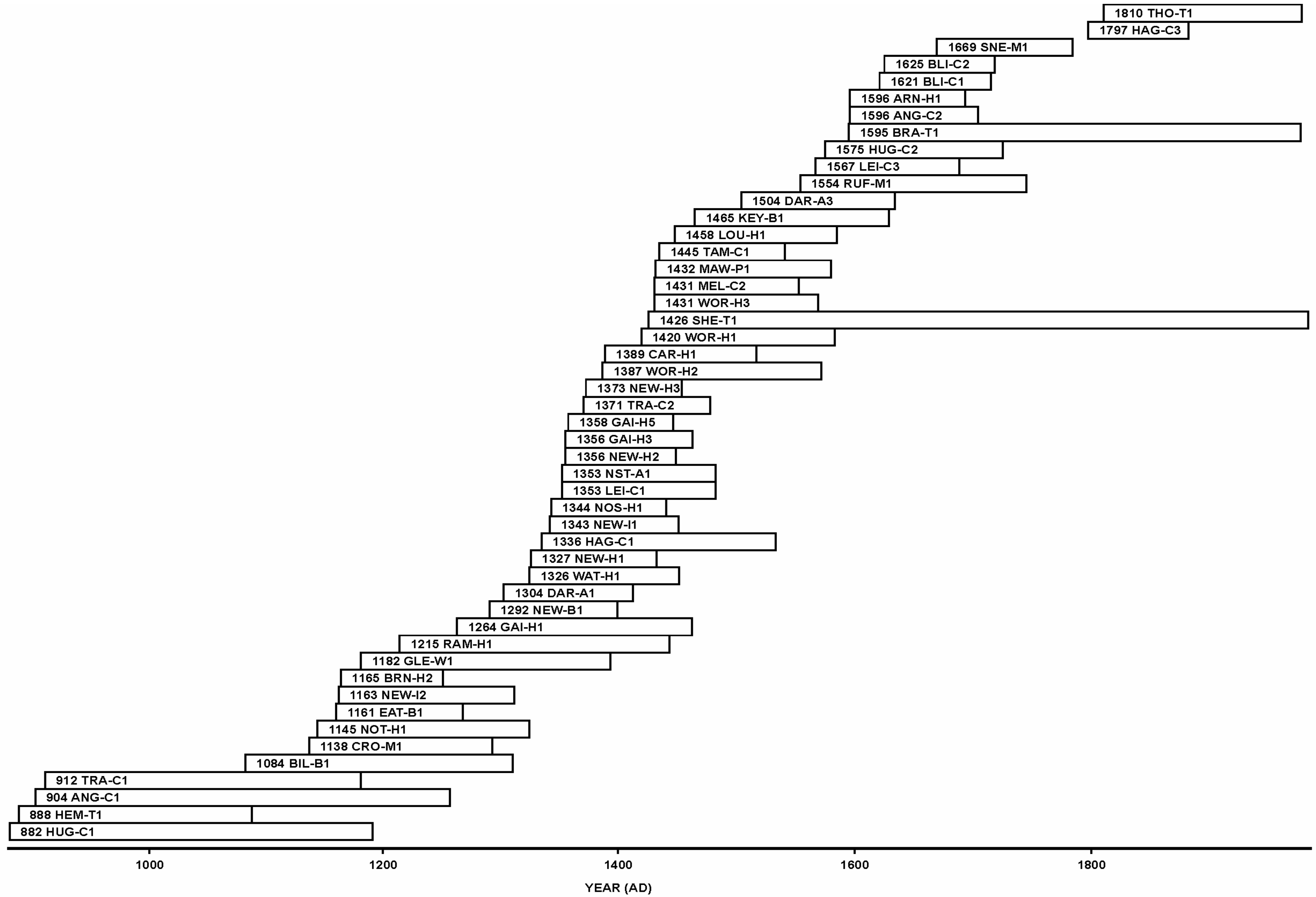
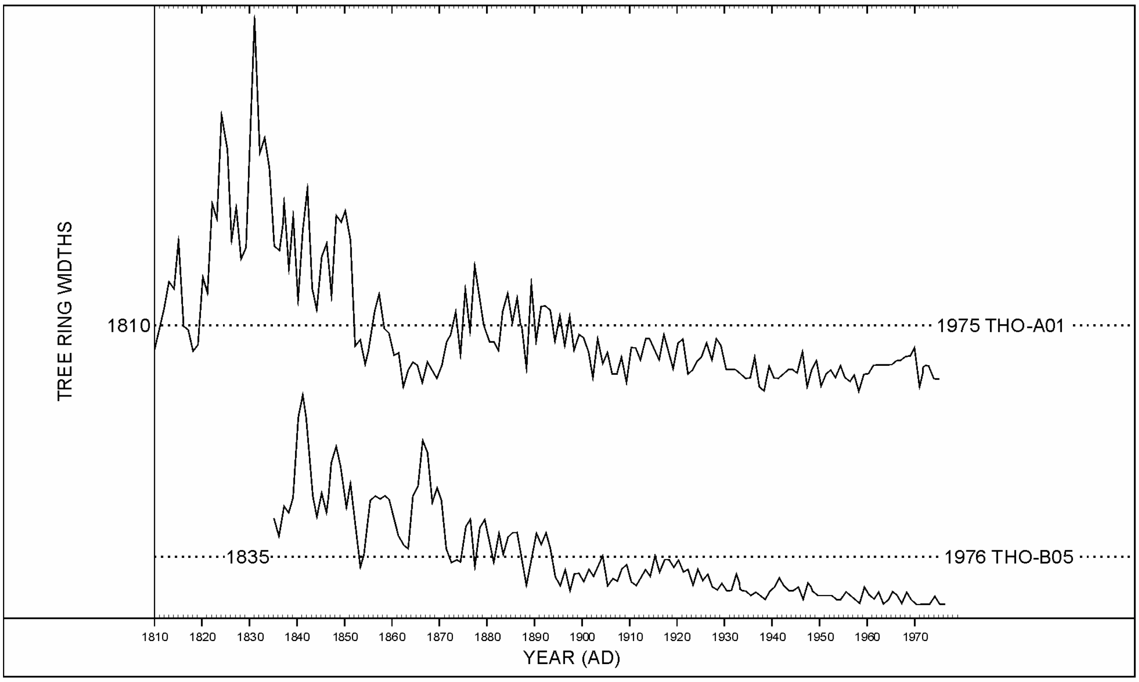


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

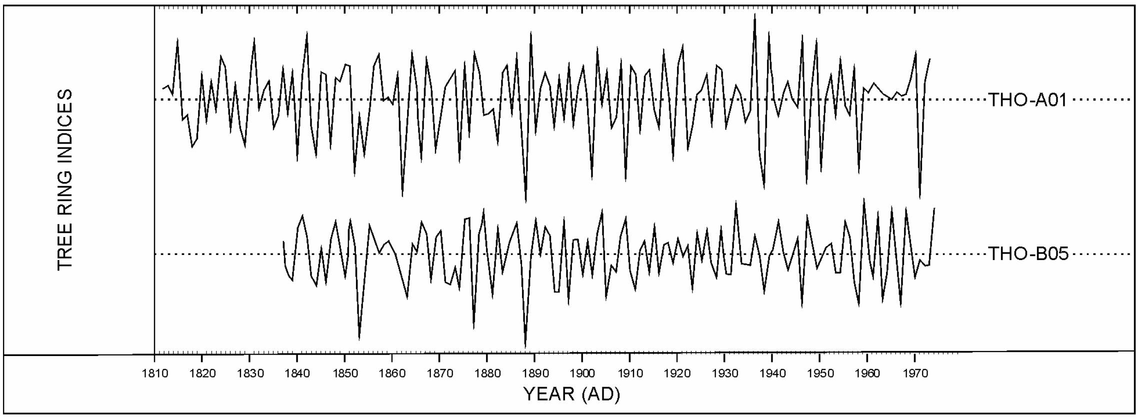


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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