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Burneside Hall
Hall Road
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Cumbria

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

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Front Cover: Exterior view of Burneside Hall from the south-west showing the tower in the foreground, the hall, and the cross-wing. Photo Alison Arnold.

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SUMMARY
Dendrochronological analysis has resulted in the dating of 39 timbers from the hall, cross-wing, and gatehouse, including the *ex situ* gates. The earliest identified timbers are within the cross-wing where the principal rafters from the westernmost truss were dated as felled during the period AD 1478–1503; the timber used within the *ex situ* gates may also date to this period, these having *terminus post quem* dates for felling of AD 1422, AD 1435, AD 1437, and AD 1472. The bulk of the dated timbers were felled approximately a century later with the majority of the timber utilised within the hall roof being felled in AD 1579–1604, although a single timber is potentially slightly later, dating to AD 1595–1620. Broadly coeval with the hall roof is a single partition timber within the hall, dated to AD 1582–1607, and the gatehouse roof and floor, dating to AD 1584–1609 and AD 1590–1615 respectively. The latest timbers identified represent a second phase of the cross-wing roof dating to AD 1612–37. These timbers are in the central area of the roof, apart from a single purlin in the western roof area. A floor beam from the first-floor structure in the central area of the cross-wing is also thought to belong to this phase of work dating to AD 1605–30, as is a single timber utilised within the hall stairs, which was felled in AD 1605–30.

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INTRODUCTION

The Scheduled Monument (LEN 1007129) and Grade II* listed Burneside Hall complex (LEN 1289216), is situated to the north-east edge of Burneside, a village located just under 3km north-northwest of Kendal in Cumbria (Figs 1–4). Burneside Hall comprises a fourteenth-century tower with the hall to its south-east, thought to have been built in the sixteenth century and expanded in the seventeenth century (Fig 4). The hall was originally at first-floor level where there is a pre-seventeenth-century panelled screen. To the south-east of the hall is the cross-wing, thought to be, potentially, of a number of building phases. Surviving on the first floor are the remains of a seventeenth-century plaster ceiling and frieze. To the south-west of the tower, approximately 30m away, is the gatehouse (Fig 4), also thought to be fourteenth century. Stretches of the curtain wall survive, which would have formed the original fortified courtyard, whilst to the front of the tower are traces of the moat that surrounded the site, and an ornamental lake with a small island.

The gatehouse is aligned north to south, but for ease of description throughout the rest of this report, a site north has been assigned with respect to the tower, hall, and cross-wing complex with the tower being at the northernmost end.

Tower

The tower has long been in a ruinous state and remains on the Heritage at Risk register. It effectively formed the solar wing of the later extant house.

Hall

The roof over the hall part of the building consists of four principal-rafter and tiebeam trusses with cranked collars and queen struts, between which are two sets of purlins and common rafters (Fig 5). Visible at ground-floor level are two of the main floor beams of the floor above (Fig 6), and there is a timber partition between the main living space and stairs (Fig 7).

Cross-wing

The roof over the cross-wing appears to be of more than one phase of construction. The only timbers of the easternmost trusses (trusses 1 and 2) currently visible are the two cranked tiebeams in a first-floor bedroom (Fig 8). Trusses 3 and 4 are two principal-rafter and tiebeam trusses with queen struts, between which are common rafters and purlins (Fig 9). Located behind a chimney is a principal-rafter and tiebeam truss with a collar; there are common rafters and two sets of purlins between this and the wall and chimney (Fig 10). There are a number of floor beams from the first floor that are visible at ground-floor level, four north-south aligned (Fig 11), and one in the western part of the wing, which is east-west aligned (Fig 12); there is a matching second-floor beam to this latter one, visible at first-floor level (Fig 13).

Gatehouse

This two-bay building is of two storeys with access to the upper floor via an external stair (Fig 14). It is open to the roof at first-floor level; this consisting of three principal-rafter and tiebeam trusses with queen struts, between which are common rafters, a single tier of purlins, and a ridgepiece (Fig 15). Gates belonging to this building have previously been removed and are stored elsewhere on the estate (Fig 16).

SAMPLING

Dendrochronological analysis was requested by Charles Smith, North West Planning Director and Principal Adviser for Heritage at Risk, Historic England, to inform an options appraisal report for the future management of the site. It was hoped that the tree-ring analysis would provide independent dating evidence to enhance understanding and significance of the complex, thereby informing its future management.

Following a detailed assessment of dendrochronological potential, 56 core samples were taken from timbers of the hall, the cross-wing, the gatehouse, and from *ex situ* gates previously removed from the gatehouse. In addition, two boards of the *ex situ* gates were measured *in situ* with a graticule. Each sample was given the code BUR-N and numbered 01–58. Further details relating to the samples can be found in Table 1. Location of samples has been marked on Figures 17–21. Trusses and floor beams have been numbered from north to south (hall and gatehouse) and from east to west (cross-wing).

At the time of the assessment the derelict tower was covered in ivy. It remains a possibility that some timbers, or timber fragments, are embedded in the walls but no timbers were visible during the assessment visit, and it was noted that the door/window lintels were stone. Thus, the tower was excluded from this analysis.

ANALYSIS AND RESULTS

Seven of the core samples (three from the hall, three from the cross-wing, and one from the gatehouse) had too few rings for secure dating and so were rejected prior to measurement. The remaining 49 core samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements, and the *in situ* measurements from the two boards, are given at the end of the report. All measurements were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 43 samples matching to form four groups.

Firstly, 33 samples matched each other (minimum t-value of 4.0) and were combined at the relevant offset positions to form BURNSQ01, a site sequence of 141 rings (Fig 22). This site sequence was compared against an extensive series of relevant reference chronologies for oak. It was found to cross-date securely and consistently at a first-ring date of AD 1468 and a last-ring date of AD 1608 (Table 2).

Six samples matched each other (minimum *t*-value of 4.5) and were again combined at the relevant offset position to form BURNSQ02, a site sequence of 147 rings (Fig 23). This site sequence was found to match the reference chronologies at a first-ring date of AD 1317 and a last-ring date of AD 1463 (Table 3).

Two further site sequences, BURNSQ03 and BURNSQ04 (minimum *t*-values of 13.2 and 7.0 respectively), each containing two samples, were also constructed (Figs 24 and 25) but, although these and the remaining eight ungrouped ring series were compared with the same extensive series of relevant reference chronologies, these could not be reliably dated and, thus, all remain undated.

INTERPRETATION

Analysis has resulted in the successful dating of 39 timbers; 13 from the hall, ten from the cross-wing, and 16 from the gatehouse and gates. To aid interpretation all dated ring series are presented by area below and in Figure 26. Felling date ranges and *terminus post quem* dates for felling have been calculated using the estimate that 95% of mature oak trees from this area have between 15 and 40 sapwood rings.

Hall

Roof

Eleven of the samples taken from this roof have been successfully dated, all of which have the heartwood/sapwood boundary.

Ten of these samples form a coherent group and the heartwood/sapwood boundary ring dates are broadly contemporary, ranging from AD 1551 (BUR-N07) to AD 1570 (BUR-N04), suggesting a single episode of felling (Table 1; Fig 26). The average heartwood/sapwood ring date is AD 1564, allowing an estimated felling date range of AD 1579–1604 to be calculated for this group of timbers.

The remaining sample (BUR-N01), from the east principal rafter of truss 1, the northernmost truss, displays a lower level of similarity to the other dated samples and has a slightly later heartwood/sapwood boundary ring date of AD 1580, giving an estimated felling date for the timber represented to within the range AD 1595–1620. This clearly overlaps the felling date range produced by the other ten samples and thus, whilst it could have been felled slightly later, it is also possible that the tree represented had either fewer than the expected number of sapwood rings or towards the lower end of the number of expected sapwood rings and could, therefore, have been part of the same episode of felling that could itself have spanned a small number of years.

If all 11 samples are assumed to be coeval, a felling date range of AD 1586–1605 is obtained, allowing for the outermost measured ring present on BUR-N01, for this group of dated timbers from the hall roof.

Partition

Only one of the samples, BUR-N55, taken from this partition has been dated. The last-measured ring on this sample, from a rail in the partition, is the heartwood/sapwood boundary and this dates to AD 1567, giving an estimated felling date for the timber represented to within the range AD 1582–1607.

Stairs

Only one of the timbers associated with the stairs, a supporting beam, has been dated with a last-measured ring date of AD 1590. This marks the heartwood/sapwood boundary and, thus, allows an estimated felling date range to be calculated of AD 1605–30.

Cross-wing

Roof

Nine of the samples taken from this roof have been dated, seven of which have the heartwood/sapwood boundary. These indicate that two separate felling episodes are represented by the dated timbers (Fig 26) as follows.

The two samples (BUR-N25 and BUR-N26) representing the principal rafters from the westernmost truss, truss 5, demonstrate that these two timbers may have been derived from the same tree (t-value = 13.8). Sample BUR-N25 has the heartwood/sapwood boundary present, dating to AD1463, which produces an estimated felling date range of AD 1478–1503 for this pair of principal rafters.

The remaining seven samples clearly form a coherent group. The heartwood/sapwood ring dates on those six samples where it is present range from AD 1595 (BUR-N18, BUR-N21) to AD 1600 (BUR-N17) suggesting that they are from a single felling episode (Table 1; Fig 26). The average of these dates is AD 1597, giving an estimated felling date range for the six timbers represented of AD 1612–37. In the absence of any trace of sapwood the seventh timber in this later group has a felled after date of AD 1597 but the analysis suggests that it is also likely to have been felled at the same time, in the range AD 1612–37.

Floor structure

Only one of the samples taken from the floor structure at first-floor level has been successfully dated. With a heartwood/sapwood boundary ring date of AD 1590, it has an estimated felling date range of AD 1605–30.

Gatehouse

Roof

Ten of the samples taken have been dated, seven of which have the heartwood/sapwood boundary ring. In all cases this is broadly contemporary, ranging from AD 1562 (BUR-N40) to AD 1574 (BUR-N34, BUR-N42), suggesting a single felling episode. The average heartwood/sapwood boundary ring for these seven samples is AD 1569, giving an estimated felling date for the timbers represented within the range AD 1584–1609.

The other three dated samples do not have the heartwood/sapwood boundary ring and so estimated felling dates cannot be calculated for them. However, with last-measured ring dates of AD 1546 (BUR-N35), AD 1551 (BUR-N39), and AD 1553 (BUR-N36), these have *terminus post quem* dates for felling of AD 1561, AD 1566, and AD 1568, respectively. These would allow them to be felled at the same time as the rest of the roof timbers, a supposition supported by the strong intra-site cross-matching (*t*-values in excess of 7.0) for these three ring series with other samples from this roof.

Floor structure

Two of the samples taken from the floor structure, a main beam and a supporting post, have been dated. These are clearly contemporary and, with an average heartwood/sapwood boundary ring date for the two samples represented of AD 1575, an estimated felling date range of AD 1590–1615 is obtained for these two timbers.

Ex situ *gates*

The samples taken from the hanging stiles and *in situ* measurements from the two boards have been dated. Unfortunately, none of these have the heartwood/sapwood boundary ring and so estimated felling date ranges cannot be calculated for them. However, with last-measured ring dates of AD 1407 (BUR-N50), AD 1420 (BUR-N49), AD 1422 (BUR-N48), and AD 1457 (BUR-N51) these are estimated to have *terminus post quem* dates for felling of AD 1422, AD 1435, AD 1437, and AD 1472, respectively. The level of cross-matching between these samples, including a *t*-value of 8.9 between BUR-N48 (a board) and BUR-N50 (hanging beam), suggests that these timbers are likely to represent a single felling episode and are all, therefore, felled after AD 1472.

DISCUSSION AND CONCLUSIONS

The earliest timbers identified through dendrochronological analysis were utilised within truss 5 in the cross-wing. At the time of sampling this truss, the westernmost one situated behind the chimney, could be seen to vary visually from those trusses in the central portion of the cross-wing, raising the possibility that it might represent a different building phase. This westernmost truss has now been shown to be over 100 years earlier than the roof timbers associated with the central area of the cross-wing, constructed from timber felled in AD 1612–37, although it should be noted that a single purlin in the westernmost area of the roof is also of this date. It is unfortunate that neither of the only two accessible timbers from the two easternmost trusses in the cross-wing, the cranked tiebeams forming site sequence BURNSQ04, could be dated, thus leaving this area of roof undated. It therefore remains a possibility that this section of the roof represents a third building phase of, as yet, unknown date in the cross-wing. What is clear, from the relative heartwood/sapwood boundary positions of the two cross-matched samples (Fig 22), is that both tiebeams were felled at the same time. The failure of this site sequence to date is most likely due to it being short, only 48 rings, and being very poorly replicated, containing only two individual sample series. A floor beam to the first floor of the cross-wing, located roughly below truss 3, can be seen to be broadly coeval with the later roof trusses, dating to AD 1605–30.

Representing a different building phase to the two identified within the cross-wing, and falling between them in date, are the timbers of the hall. The roof timbers were felled in AD 1579–1604, with the possible exception of the east principal rafter from truss 1, represented by sample BUR-N01, which has a slightly later but nevertheless overlapping felling date range of AD 1595–1620. Sample BUR-N01 does not match the other samples from the hall roof quite as well as the rest of the timber, which may indicate that it is from a different source but, whilst it may be slightly later, it is not necessarily so. It may simply be that the tree represented by this sample had a sapwood complement outside of the 95% range applied.

A rail in the partition between the main-living space and the stairs in the hall at ground-floor level is likely to be coeval with the roof timbers, dating to AD 1582–1607. Only one beam from the stairs themselves is dated; this is a supporting beam now known to have been felled in AD 1605–30, making it broadly coeval with the later phase of timber from the cross-wing roof and the first-floor beam, also in the cross-wing.

Also belonging to the late-sixteenth/early seventeenth-century building phase, and therefore broadly contemporary with the hall roof and partition, are timbers of the roof and floor of the gatehouse, being felled in AD 1584–1609 and AD 1590–1615, respectively. These results suggest that the floor and roof of the gatehouse are broadly contemporary. Indeed, one of the queen struts from the roof (BUR-N34), and one of the supporting posts from the floor structure in the gatehouse (BUR-N45), match each other at a level high enough (t-value = 11.0) to suggest that these two timbers may have been cut from the same tree.

High level cross-matching has been noted above, between the principal rafters from truss 5 in the cross-wing and a queen strut and supporting post for the floor structure in the gatehouse, but there are a number of other possible same-tree pairs of timbers, including the undated principal rafters (BUR-N15 and BUR-N16) of truss 3 in the cross-wing (t-value = 13.2), the tiebeams (BUR-N08 and BUR-N11) from trusses 3 and 4 in the hall roof (t-value = 11.9), and from the principal rafters of truss 2 (BUR-N04 and BUR-N05) in the hall roof (t-value = 10.3). These, combined with the overall level of cross-matching within the main phases of felling identified suggests that the timbers were derived for each phase of construction from a single, albeit potentially large, woodland area. The two dated site sequences, BURNSQ01 and BURNSQ02 tend to show the highest levels of similarity with reference chronologies from the surrounding regions (Tables 2 and 3), although BURNSQ01 is very well-replicated and, hence, does match strongly further afield as well, suggesting that the woodland sources exploited for the construction of Burneside Hall were probably relatively local.

It is unfortunate that the Tower was excluded from this programme of dendrochronological analysis but it ought to be reconsidered if timbers are revealed during future works. Similarly sampling of additional elements associated with the easternmost section of the cross-wing roof, from which only two tiebeams that remain undated were accessible, should be considered if access becomes possible.

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TABLES

Table 1: Details of samples taken from Burneside Hall, Burneside, near Kendal, Cumbria

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
HALL						
Roof						
BUR-N01	East principal rafter, truss 1	68	05	1518	1580	1585
BUR-N02	West principal rafter, truss 1	58	h/s	----	----	----
BUR-N03	Collar, truss 1	63	h/s	1494	1556	1556
BUR-N04	East principal rafter, truss 2	84	03	1490	1570	1573
BUR-N05	West principal rafter, truss 2	76	02	1496	1569	1571
BUR-N06	Tiebeam, truss 2	70	12	1499	1556	1568
BUR-N07	East principal rafter, truss 3	60	h/s	1492	1551	1551
BUR-N08	Tiebeam, truss 3	73	h/s	1497	1569	1569
BUR-N09	East principal rafter, truss 4	84	h/s	1483	1566	1566
BUR-N10	West principal rafter, truss 4	62	h/s	1500	1561	1561
BUR-N11	Tiebeam, truss 4	73	h/s	1498	1570	1570
BUR-N12	East lower purlin, truss 1–3	67	h/s	1502	1568	1568
First-floor structure						
BUR-N52	Main beam	NM	--	----	----	----
Partition, main living space to stairs, ground floor						
BUR-N53	Cill beam	NM	--	----	----	----
BUR-N54	Stud	NM	--	----	----	----
BUR-N55	Rail	84	h/s	1484	1567	1567
Stairs						
BUR-N56	Newel post	93	h/s	----	----	----
BUR-N57	Supporting beam	84	h/s	1507	1590	1590
BUR-N58	Hanging stile	62	h/s	----	----	----
CROSS-WING						
Roof						

BUR-N13	Tiebeam, truss 1	48	h/s	----	----	----
BUR-N14	Tiebeam, truss 2	48	h/s	----	----	----
BUR-N15	North principal rafter, truss 3	117	h/s	----	----	----
BUR-N16	South principal rafter, truss 3	102	h/s	----	----	----
BUR-N17	Tiebeam, truss 3	84	08	1525	1600	1608
BUR-N18	North upper purlin, truss 3-4	114	h/s	1482	1595	1595
BUR-N19	South upper purlin, truss 3-4	114	h/s	1485	1598	1598
BUR-N20	North principal rafter, truss 4	109	h/s	1488	1596	1596
BUR-N21	South principal rafter, truss 4	110	h/s	1486	1595	1595
BUR-N22	Tiebeam, truss 4	97	h/s	----	----	----
BUR-N23	South upper purlin, truss 4 – west wall	80	--	1503	----	1582
BUR-N24	North lower purlin, east – truss 5	105	02	1495	1597	1599
BUR-N25	North principal rafter, truss 5	68	h/s	1396	1463	1463
BUR-N26	South principal rafter, truss 5	68	--	1384	----	1451
First floor structure						
BUR-N27	Beam 4 (kitchen)	NM	--	----	----	----
BUR-N28	Beam 3 (kitchen)	109	05	1487	1590	1595
BUR-N29	Beam 2 (bathroom)	NM	--	----	----	----
BUR-N30	Beam 1 (bathroom)	NM	--	----	----	----
Second floor structure						
BUR-N31	Ceiling beam	86	h/s	----	----	----
Gatehouse						
BUR-N32	West principal rafter, truss 1	70	h/s	1499	1568	1568
BUR-N33	East queen strut, truss 1	59	h/s	1515	1573	1573
BUR-N34	West queen strut, truss 1	57	h/s	1518	1574	1574
BUR-N35	East principal rafter, truss 2	61	--	1486	----	1546
BUR-N36	West principal rafter, truss 2	58	--	1496	----	1553
BUR-N37	Tiebeam, truss 2	75	h/s	1491	1565	1565
BUR-N38	West queen strut, truss 2	61	h/s	1509	1569	1569
BUR-N39	East principal rafter, truss 3	48	--	1504	----	1551
BUR-N40	West principal rafter, truss 3	58	h/s	1505	1562	1562
BUR-N41	East purlin	NM	--	----	----	----

BUR-N42	West purlin	64	h/s	1511	1574	1574
Floor structure						
BUR-N43	North-south beam	106	h/s	1468	1573	1573
BUR-N44	North supporting post	76	h/s	----	----	----
BUR-N45	South supporting post	85	h/s	1492	1576	1576
BUR-N46	Joist 5	47	--	----	----	----
BUR-N47	Joist 6	49	h/s	----	----	----
Ex-situ gates						
BUR-N48	Board	76	--	1347	----	1422
BUR-N49	Board	55	--	1366	----	1420
BUR-N50	Hanging beam – left gate	91	--	1317	----	1407
BUR-N51	Hanging beam – right gate	97	--	1361	----	1457

Key:
NM = not measured;
h/s = the heartwood/sapwood boundary is the last-measured ring

Table 2: Results of the cross-matching of site sequence BURNSQ01 and relevant reference chronologies when the first-measured ring date is AD 1468 and the last-measured ring date is AD 1608

Reference	*t*-value	Span of chronology (AD)	Reference
Tonge Hall, Rochdale, Lancashire	8.1	1449–1687	Arnold and Howard 2014a
Church of St Andrew (bellframe), Welham, Leicestershire	7.4	1443–1633	Arnold *et al* 2005
The Reader's House, Ludlow, Shropshire	6.8	1406–1614	Bridge and Miles 2011
Dandra Garth, Garsdale, Cumbria	6.7	1373–1635	Arnold and Howard 2014b
Fellow's Quad, Merton College, Oxfordshire	6.6	1442–1608	Miles and Worthington 2006
Belfast chronology	6.3	1001–1970	Baillie 1977
Docton Court, Appledore, Devon	6.1	1440–1581	Arnold and Howard 2012
Bramall Hall, Bramall, Greater Manchester	6.0	1359–1590	Arnold *et al* 2013
Langley Gatehouse, Shropshire	5.7	1491–1600	Hillam and Groves 1993
Dilston Castle, Dilston Hall, Corbridge, Northumberland	5.5	1402–1611	Arnold *et al* 2003

Table 3: Results of the cross-matching of site sequence BURNSQ02 and relevant reference chronologies when the first-measured ring date is AD 1317 and the last-measured ring date is AD 1463

Reference	*t*-value	Span of chronology	Reference
Nappa Hall, Askrigg, North Yorkshire	6.1	1300–1476	Arnold and Howard 2013
Blanchland Abbey Gatehouse, Northumberland	5.6	1326–1532	Arnold *et al* 2009
Nether Levens Hall, Kendall, Cumbria	5.6	1271–1410	Howard *et al* 1991
Dandra Garth, Garsdale, Cumbria	5.5	1373–1635	Arnold and Howard 2014b
Dacre Hall, Lanercost Priory, Brampton	5.5	1350–1504	Arnold *et al* 2004a
Hopwood Hall, Rochdale, Manchester	5.4	1287–1427	Howard *et al* 2003
Wetheral Priory Gatehouse, Wetheral, Cumbria	5.3	1386–1449	Arnold *et al* 2004b
Drogheda Boat, Co Louth, Republic of Ireland	5.3	1390–1530	Brown pers comm
Hallfield House, Bradfield, South Yorkshire	5.3	1320–1445	Hillam 1981
Whitwood Farm, Yorkshire	5.0	1316–1444	Arnold and Howard 2010 unpubl

FIGURES

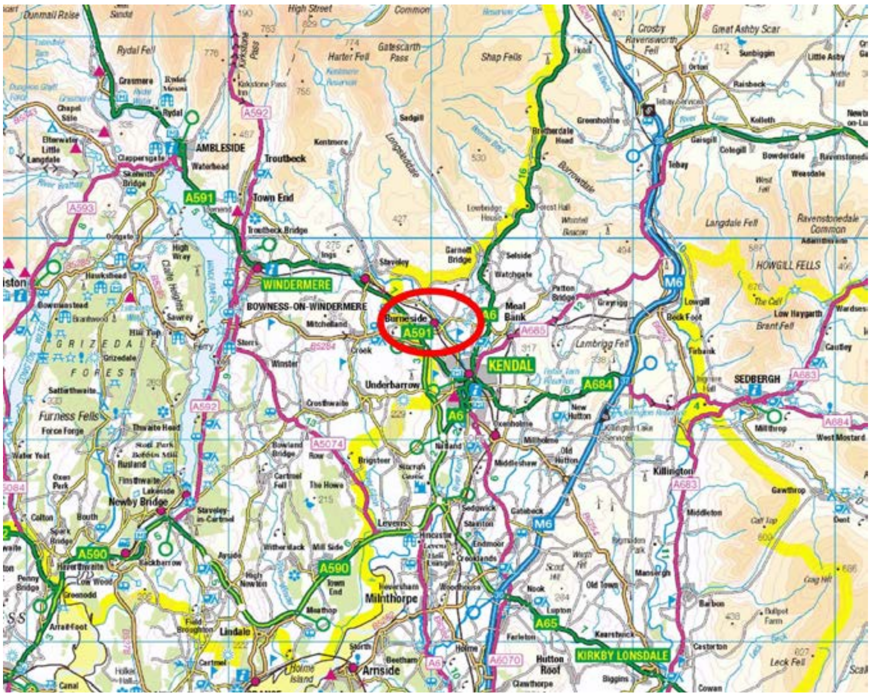

Figure 1: Map to show the general location of Burneside, Cumbria (red ellipse). © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

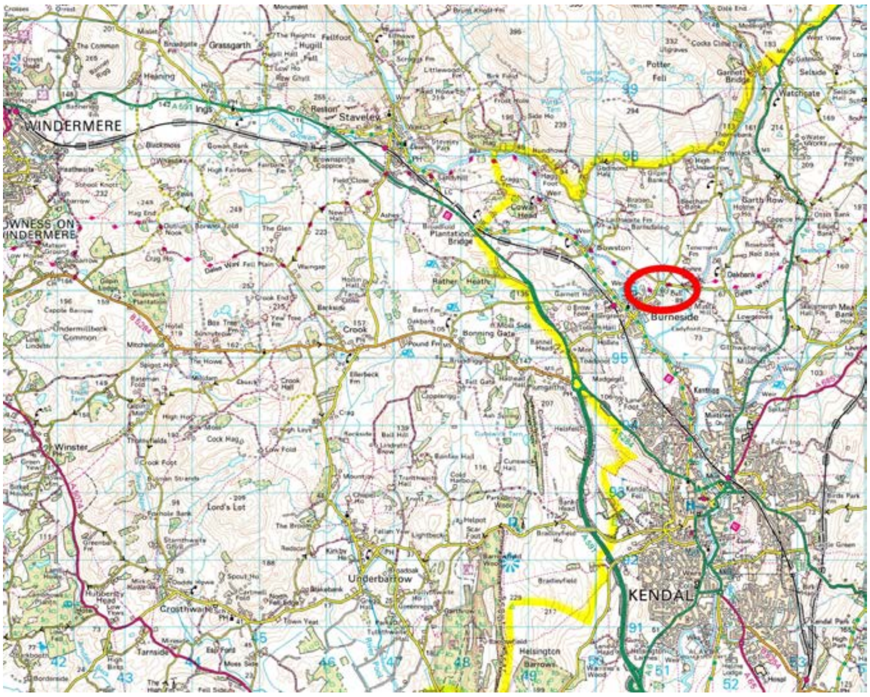

Figure 2: Map to show the general location of the Burneside Hall complex (red ellipse) in relation to the settlement of Burneside. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Map to show the detailed location of the Burneside Hall complex (red ellipse) in relation to the settlement of Burneside. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

Figure 4: Map to show the Burneside Hall complex, with the tower (blue), hall (red), cross-wing (yellow), and gatehouse (green) marked. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

Figure 5: Hall roof, with truss 3 in the foreground, photograph taken from the south (Alison Arnold)

Figure 6: Hall - east-west first-floor beam, visible from the ground floor, photograph taken from the north-west (Alison Arnold)

Figure 7: Hall - partition between the lounge and stairs, photograph taken from the south (Alison Arnold)

Figure 8: Cross-wing - the tiebeams of trusses 1 and 2, photograph taken from the west (Alison Arnold)

Figure 9: Cross-wing truss 4, photograph taken from the east (Alison Arnold)

Figure 10: Cross-wing truss 5, photograph taken from the west (Alison Arnold)

Figure 11: Cross-wing - north-south first floor beams, visible on the ground floor, photograph taken from the west (Alison Arnold)

Figure 12: Cross-wing - east-west first-floor beam, visible from the ground floor, photograph taken from the south-east (Alison Arnold)

Figure 13: Cross-wing - second-floor beam, visible from the first floor, photograph taken from the east (Alison Arnold

Figure 14: The Gatehouse, photograph taken from the north-east (Alison Arnold

Figure 15: The Gatehouse, truss 2 in foreground, photograph taken from (Alison Arnold)

Figure 16: Gatehouse gates

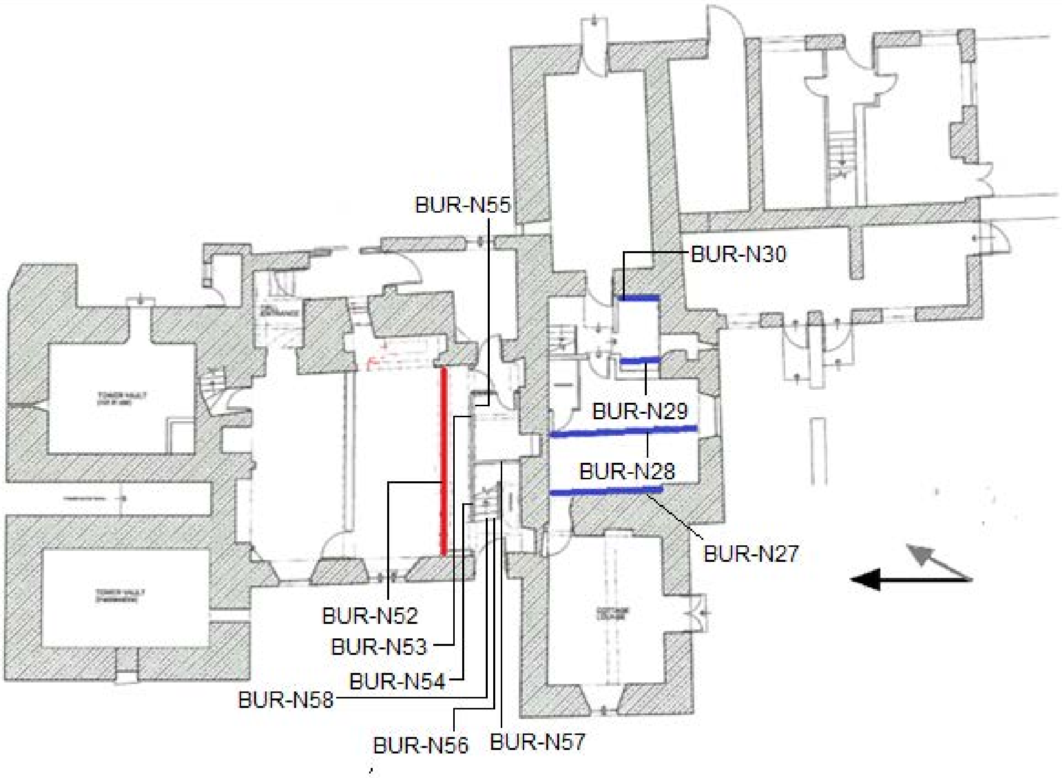

Figure 17: Ground-floor plan showing the location of the sampled timbers, samples BUR-N27–BUR-N30 and BUR-N52–BUR-N58 (after Crosby Granger Architects 2018)

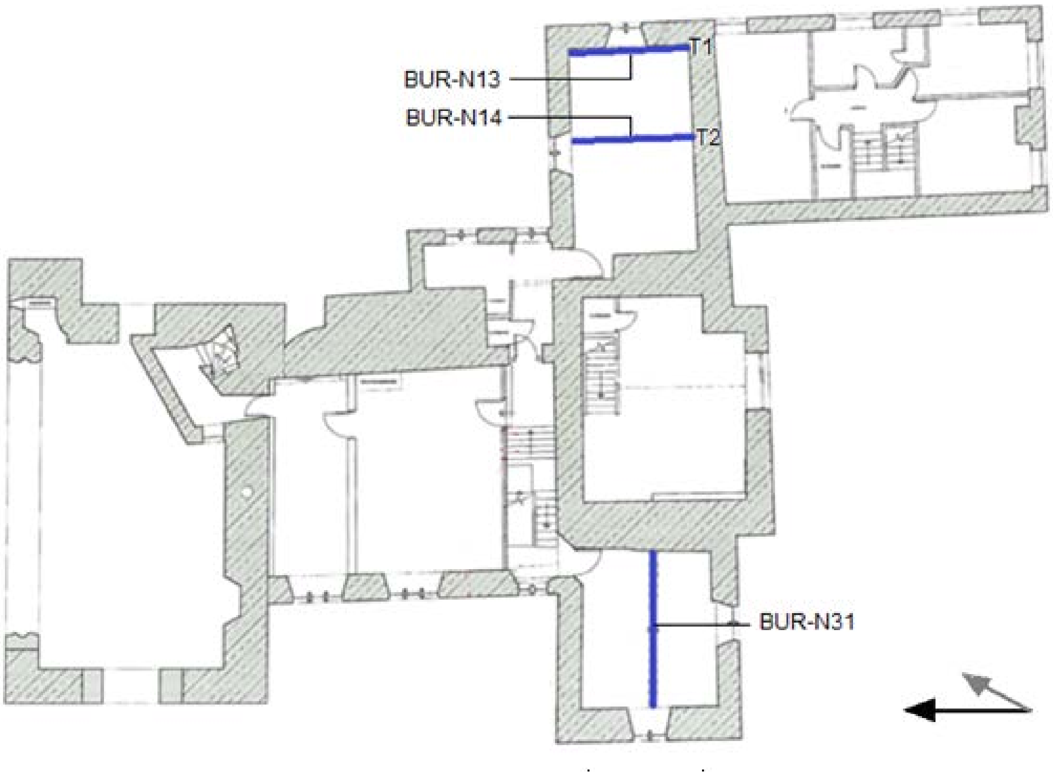

Figure 18: First-floor plan showing the location of the sampled timbers, samples BUR-N13, BUR-N14 and BUR-N31 (after Crosby Granger Architects 2018)

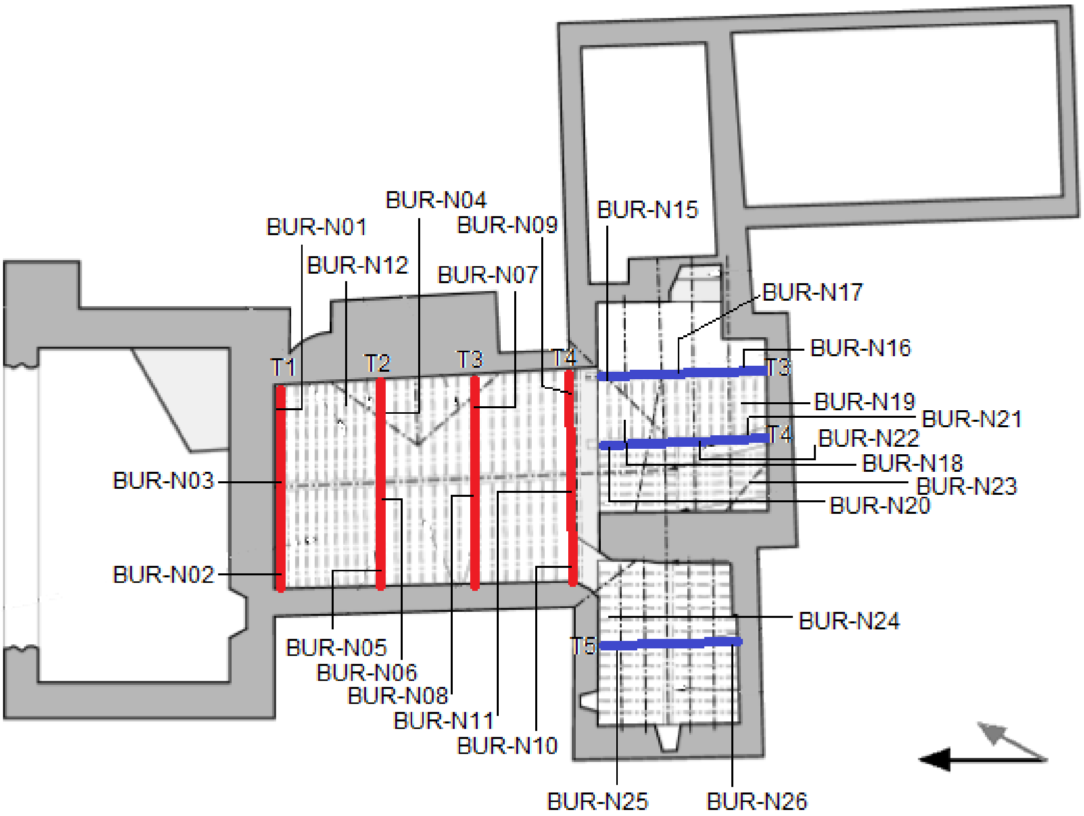

Figure 19: Roof level plan showing the location of the sampled timbers, samples BUR-N01–BUR-N12 and BUR-N15–BUR-N26

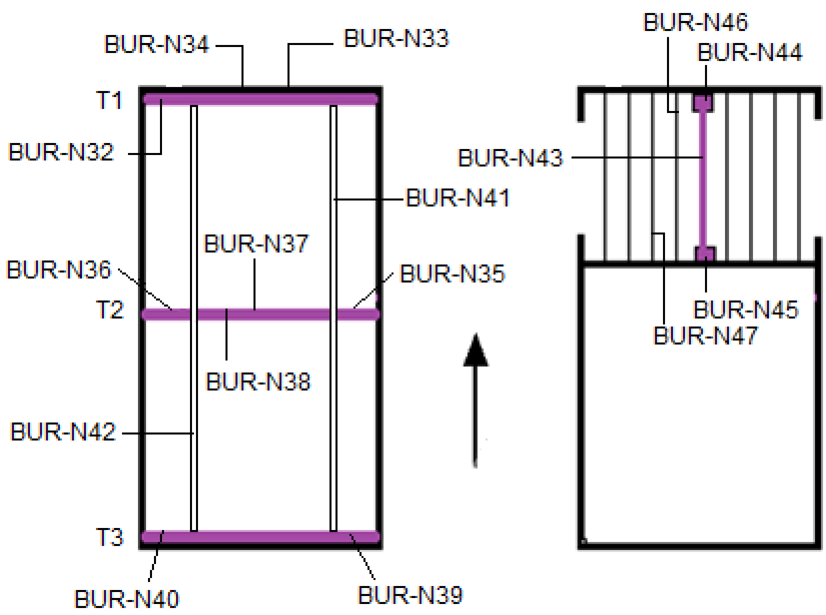

Figure 20: Sketch plan of the gatehouse, showing the location of sampled timbers, samples BUR-N32–BUR-N47

Figure 21: Photographs of the ex-situ gates, showing the location of samples BUR-N48-51 (Alison Arnold)

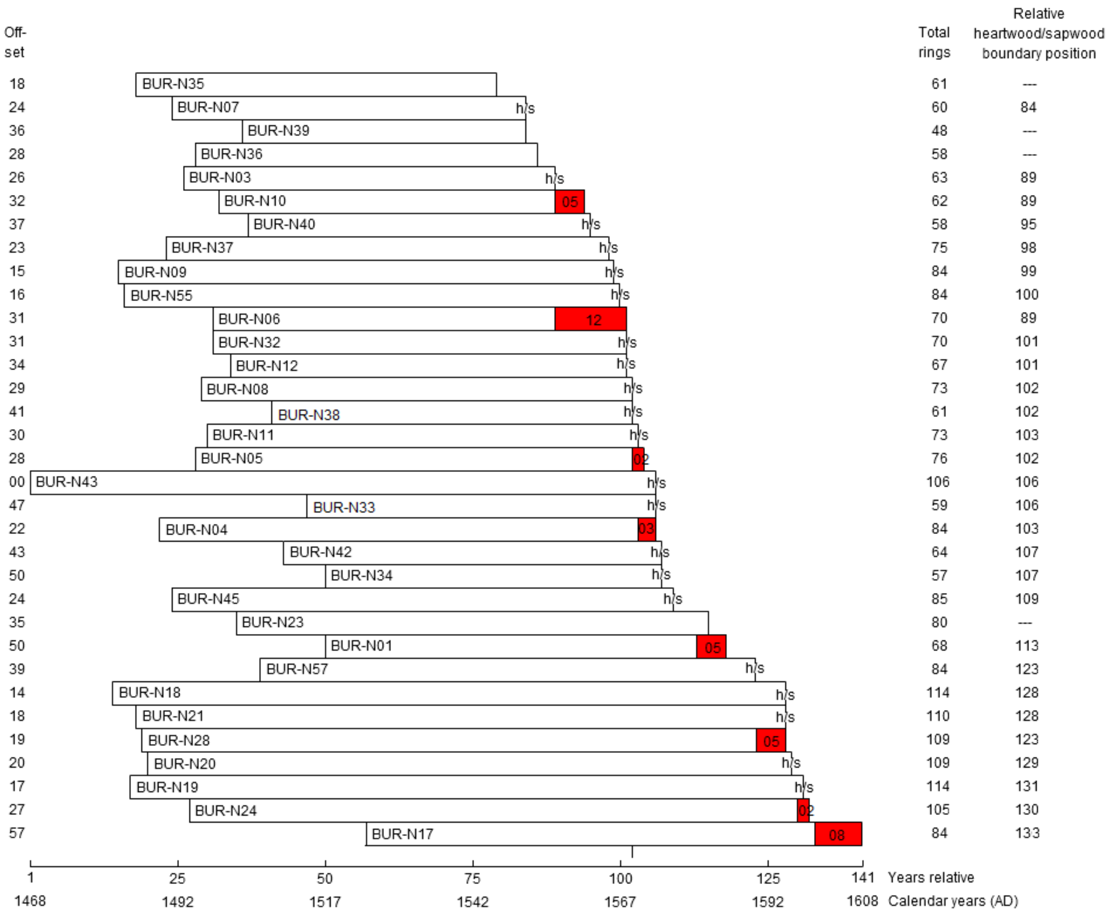

Figure 22: Bar diagram of samples in site sequence BURNSQ01. White bar = heartwood rings; red bar = sapwood rings; hs = heartwood/sapwood boundary ring is the last measured ring present; nn = number of sapwood rings present

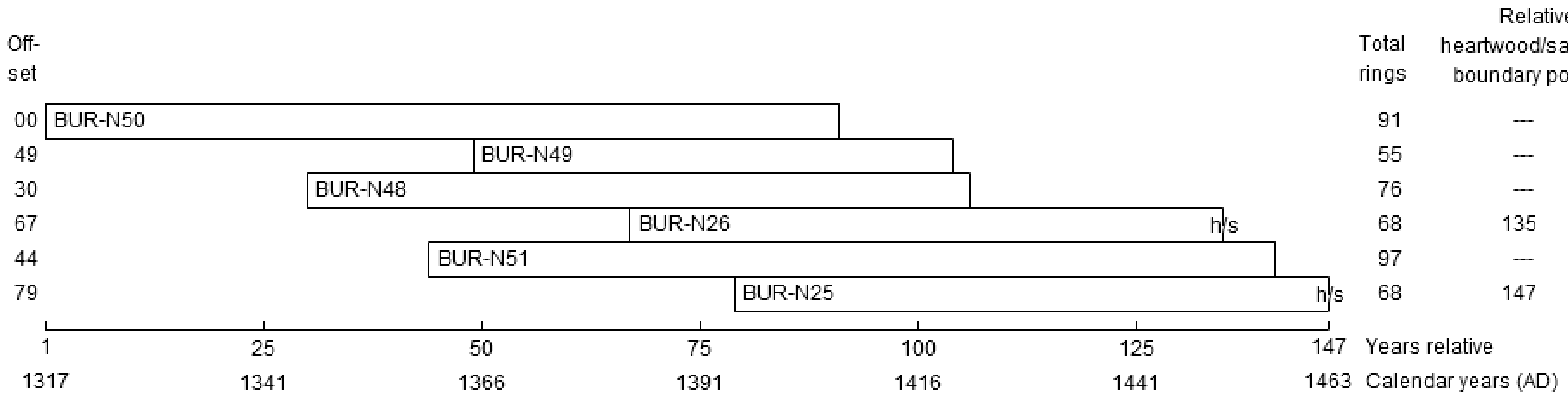

Figure 23: Bar diagram to show the relative position of samples in site sequence BURNSQ02. White bar = heartwood rings; hs = heartwood/sapwood boundary ring is the last measured ring present

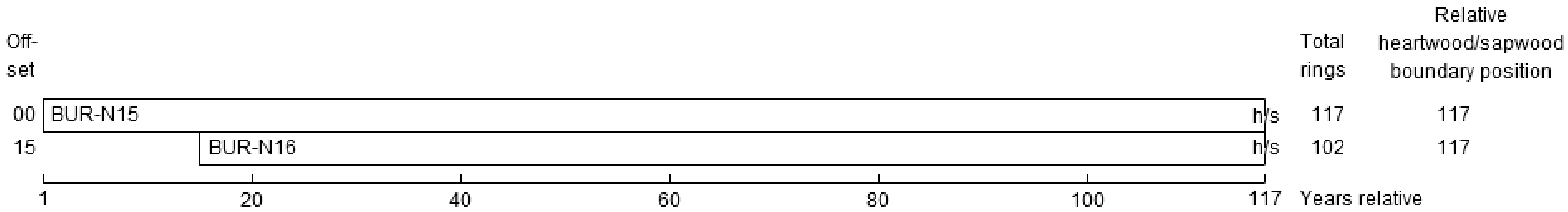

Figure 24: Bar diagram to show the relative position of samples in undated site sequence BURNSQ03. White bar = heartwood rings; hs = heartwood/sapwood boundary ring is the last measured ring present

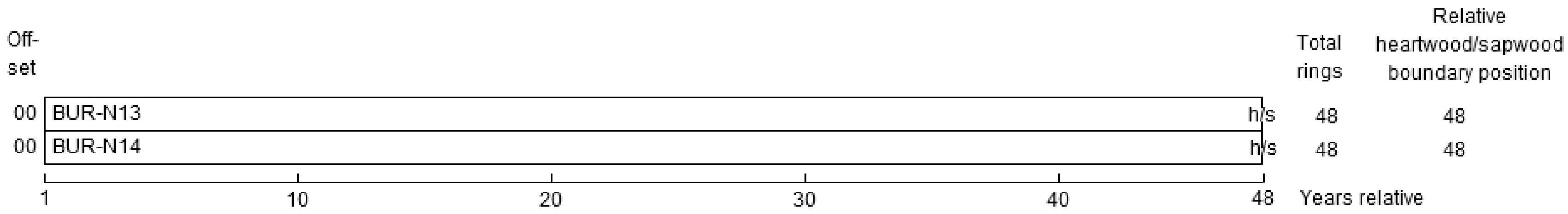

Figure 25: Bar diagram to show the relative position of samples in undated site sequence BURNSQ04. White bar = heartwood rings; hs = heartwood/sapwood boundary ring is the last measured ring present

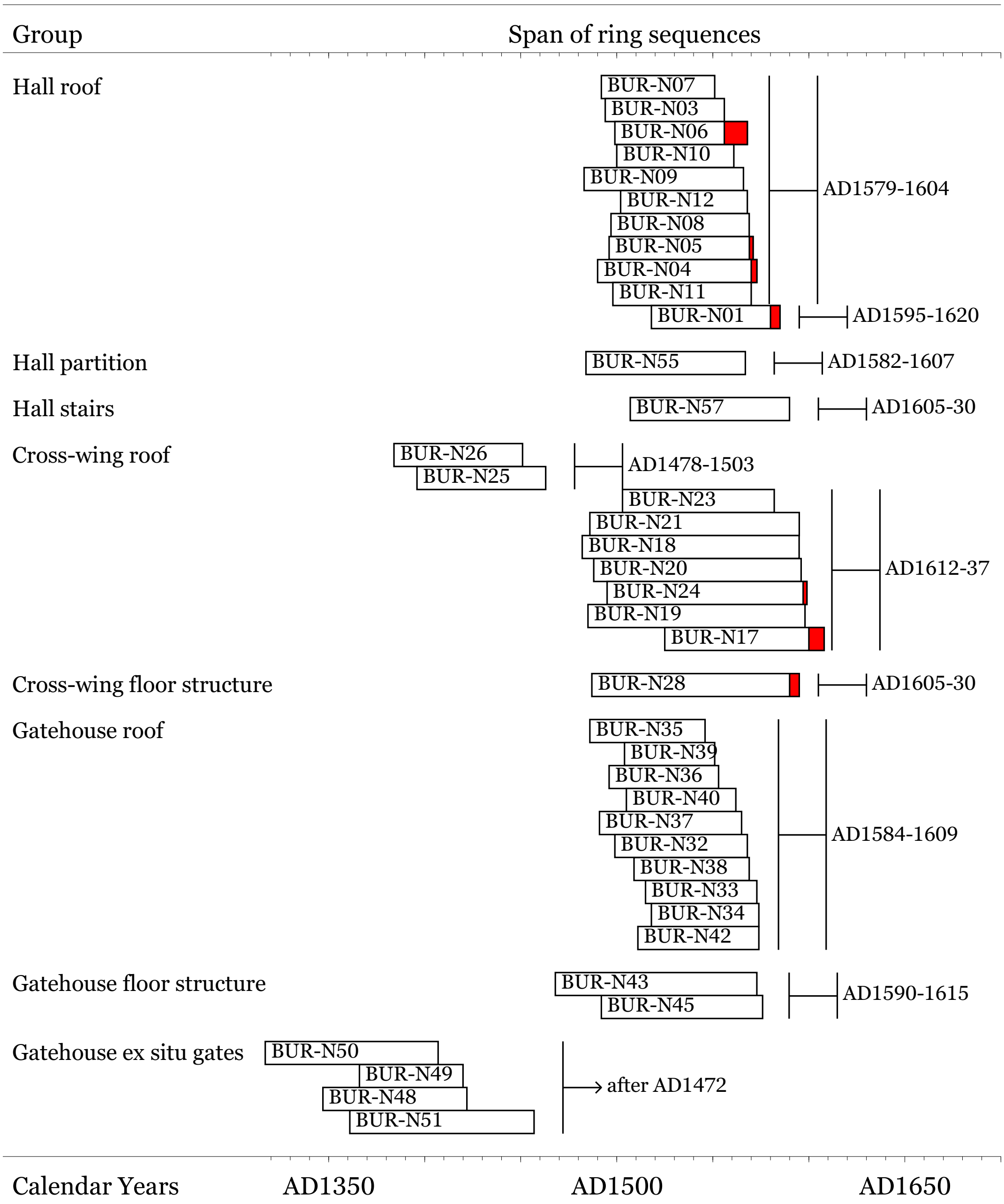

Figure 26: Bar diagram of dated samples, sorted by area with associated felling date ranges / felled after dates. White bar = heartwood rings; red bar = sapwood rings

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BUR-N01A 68
383 441 314 330 411 332 368 306 385 463 394 429 465 621 602 481 421 574 518 257
244 277 350 228 143 165 174 165 179 204 183 227 215 276 205 267 277 202 165 176
223 304 366 237 268 271 234 205 241 210 283 172 171 243 250 351 180 216 296 247
222 361 417 165 60 49 46 69
BUR-N01B 68
354 453 271 336 415 342 375 325 373 471 394 418 478 623 602 484 413 574 513 271
249 273 336 228 145 179 171 158 183 201 161 187 209 288 206 287 277 217 149 175
220 310 371 222 268 266 247 220 242 199 270 172 177 236 270 352 179 209 292 251
227 359 406 176 52 43 52 81
BUR-N02A 58
449 472 452 350 459 406 349 397 363 350 305 408 364 388 290 219 239 227 215 239
211 242 166 151 168 227 239 261 273 347 253 321 262 255 305 260 235 196 186 276
273 304 235 297 290 276 247 157 189 246 251 197 178 199 154 175 273 280
BUR-N02B 58
421 476 452 352 453 409 353 399 354 309 313 413 394 377 304 207 226 220 241 243
227 251 166 148 171 221 248 256 280 343 252 341 259 256 303 268 237 197 186 285
277 310 247 309 281 280 230 144 209 247 269 205 180 209 162 204 254 294
BUR-N03A 63
180 213 286 200 199 294 245 250 278 291 307 345 369 248 242 227 275 297 325 295
208 308 306 270 275 288 349 194 318 236 183 316 348 311 235 238 395 433 359 357
361 417 383 437 263 478 600 417 285 293 279 518 444 417 151 60 73 52 46 39
45 34 49
BUR-N03B 63
159 231 299 210 204 298 252 252 279 307 355 355 364 270 235 225 269 301 327 299
201 313 310 269 259 288 343 207 321 244 185 331 379 326 245 235 379 440 356 352
375 438 394 444 265 481 593 424 285 281 254 500 443 416 155 65 78 51 44 55
42 35 36
BUR-N04A 84
299 251 248 267 238 285 318 196 268 357 199 190 229 256 281 297 326 500 438 348
402 473 484 319 373 336 365 407 353 297 267 368 394 266 317 402 363 132 77 77
122 111 138 158 229 260 287 242 184 274 83 77 34 83 76 98 135 147 120 209
229 337 394 323 231 220 180 153 207 268 264 371 318 326 330 179 65 57 45 72
81 113 134 148
BUR-N04B 84
302 255 244 274 209 277 308 201 265 352 204 191 227 250 288 294 326 495 455 341
406 459 466 321 378 338 367 400 353 290 259 371 398 267 294 394 402 130 76 82
116 107 158 138 214 263 286 236 171 263 78 71 44 91 66 112 137 140 116 212
229 339 388 339 226 222 175 160 208 268 262 377 318 320 329 180 78 53 50 75
94 109 138 144
BUR-N05A 76
349 201 321 348 199 176 183 247 263 293 361 499 506 465 579 485 439 306 347 348
395 389 356 345 409 321 392 265 242 259 247 118 58 67 92 110 135 132 182 250
219 239 211 222 70 70 42 69 85 134 121 170 100 135 232 367 205 250 146 207
128 186 288 254 227 355 303 371 292 134 51 38 52 64 99 106

BUR-N05B 76
344 208 311 362 201 187 187 244 273 297 374 495 497 464 584 487 430 308 356 342
396 388 363 343 410 321 393 258 245 242 251 122 64 88 87 115 118 139 160 257
219 232 200 216 73 74 42 71 73 141 122 153 107 144 230 368 203 243 142 213
139 197 277 237 224 351 304 360 287 131 52 45 47 61 108 104
BUR-N06A 70
494 410 399 411 373 445 431 416 506 429 366 229 162 163 167 153 183 222 209 225
275 260 256 233 205 172 253 258 192 132 123 145 159 212 178 183 236 285 230 238
314 121 145 71 95 119 161 154 154 149 213 186 220 178 160 77 50 57 45 43
43 55 79 129 163 107 62 85 154 104
BUR-N06B 70
505 408 414 397 385 433 426 434 468 426 378 218 174 161 144 147 193 205 225 207
249 206 256 248 195 162 256 266 189 141 115 138 145 204 193 185 249 278 234 220
317 112 140 72 101 126 164 150 161 140 219 180 227 180 179 71 53 45 52 48
44 57 76 132 162 105 65 84 161 102
BUR-N07A 60
371 420 492 455 504 341 370 402 395 375 329 356 384 362 318 122 97 101 131 143
190 152 140 225 229 243 146 188 137 196 256 154 125 305 256 224 181 136 207 257
263 250 195 308 323 324 271 385 319 341 272 375 318 300 307 321 114 54 51 66
BUR-N07B 60
366 403 491 434 499 344 370 413 395 372 323 357 388 364 306 126 93 102 131 144
190 154 137 223 242 233 147 191 135 200 256 155 127 300 261 226 181 155 201 256
260 281 206 320 342 315 269 393 321 330 269 389 323 307 305 322 107 59 51 69
BUR-N08A 73
229 241 359 340 309 298 351 327 402 317 358 449 321 389 437 432 287 273 341 297
363 395 348 374 388 406 337 410 500 488 477 170 56 47 95 65 55 65 111 126
179 150 169 223 186 206 227 283 273 244 255 111 43 45 43 48 64 66 48 36
30 53 53 34 59 103 87 161 64 70 108 117 118
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165 154 168 223 186 210 213 286 279 244 267 114 44 49 42 48 64 64 50 35
34 51 48 37 53 103 93 158 60 73 112 117 114
BUR-N09A 84
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230 242 262 206 351 334 346 249 385 300 269 220 247 331 284 184 262 185 167 214
106 129 267 179 216 250 213 158 245 167 206 205 319 244 231 114 178 74 67 60
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182 194 121 149
BUR-N09B 84
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224 257 265 211 353 330 347 253 389 289 279 218 241 336 273 182 279 200 166 210
105 124 271 177 215 255 217 167 229 182 200 203 311 247 227 121 176 72 73 51
71 80 113 123 150 104 188 186 322 373 370 105 68 55 78 100 122 123 175 195
187 189 115 145
BUR-N10A 62
201 198 165 197 187 150 186 301 241 189 273 297 258 259 261 256 217 202 143 273
172 297 273 192 188 299 212 251 284 205 209 245 160 211 211 274 261 177 133 155
73 88 60 71 63 60 76 72 54 118 140 175 176 204 70 52 53 54 77 72
67 94

BUR-N10B 62
212 208 157 202 177 150 187 322 251 215 285 299 263 251 255 250 225 215 135 280
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77 84 62 74 61 61 80 65 63 113 136 174 162 203 77 53 47 57 74 77
69 98
BUR-N11A 73
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341 337 317 247 291 234 228 199 239 266 102 58 48 86 77 70 72 126 134 164
163 151 175 180 140 185 239 235 193 217 105 64 85 88 86 104 119 88 93 76
75 105 85 112 133 125 112 71 96 159 109 136 138
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71 103 77 117 131 125 119 74 90 154 111 134 150
BUR-N12A 67
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159 110 103 161 180 131 147 143 112 146 103 101 101 159 125 124 92 110 141 137
103 125 125 151 167 177 171 170 148 190 129 115 104 86 58 77 42 51 51 56
63 52 65 59 61 48 69
BUR-N12B 67
135 175 206 228 151 217 140 145 121 114 116 101 72 101 126 82 87 83 84 118
154 102 97 162 172 140 148 142 96 151 104 108 106 140 116 118 84 117 137 144
92 122 113 156 155 174 164 168 141 182 130 117 104 83 63 72 40 61 46 59
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BUR-N13A 48
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453 587 686 598 625 531 519 529
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243 173 477 523 522 413 427 557 508 637 457 563 591 235 292 331 438 467 560 428
453 583 675 606 626 534 515 530
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385 300 395 415 414 326 281 399 430 427 338 403 368 263 317 292 250 260 298 209
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382 379 419 319 304 287 272 373 284 325 323 405 502 432 316 378 427 296 383 368
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BUR-N15A 117
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BUR-N15B 117
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BUR-N16A 102
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109 102
BUR-N16B 102
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197 146 181 140 172 165 131 82 81 75 116 175 180 128 220 73 39 29 35 28
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52 78 75 78
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161 152 164 156 194 150 164 178 188 138 165 150 160 202 183 165 173 192 160 157
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42 44 43 54 67 70
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BUR-N32A 70
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303 257 241 287 196 213 202 245 194 212 195 289 298 244 192 235 231 253 228 67
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BUR-N34A 57
189 178 175 240 258 214 219 310 290 236 259 274 304 262 235 218 189 257 209 218
188 271 280 205 199 203 210 230 240 255 216 254 239 319 213 209 168 156 77 59
135 164 184 213 197 163 254 171 158 170 100 228 238 187 128 144 133
BUR-N34B 57
178 182 176 246 249 208 224 321 287 239 263 282 303 257 237 221 184 260 206 217
195 262 280 211 196 205 207 234 237 257 221 254 242 313 219 208 166 157 74 62
134 163 181 216 201 157 252 176 155 170 99 231 237 190 137 142 105
BUR-N35A 61
216 245 161 195 219 206 215 192 181 243 321 230 211 260 254 223 288 385 402 243
245 266 280 283 165 264 180 135 177 105 173 146 141 214 238 242 244 147 173 173
157 185 194 130 198 170 149 109 146 162 250 135 62 54 55 78 71 121 109 90
114

BUR-N35B 61
202 251 157 198 215 208 200 188 183 246 322 227 206 266 259 228 286 386 400 247
268 254 280 282 161 265 177 133 189 94 173 149 145 215 229 245 246 144 173 166
157 194 189 128 200 175 152 116 150 153 251 132 64 56 51 79 70 131 110 91
109
BUR-N36A 58
247 295 298 344 352 274 362 363 315 185 148 197 284 272 249 305 261 272 342 243
295 273 294 432 442 422 437 290 261 308 401 278 350 286 297 364 359 216 250 211
232 236 72 82 74 99 84 168 137 100 116 163 142 237 217 364 207 289
BUR-N36B 58
254 296 293 350 342 285 363 383 338 196 147 187 287 309 275 327 273 242 351 241
291 281 296 420 424 406 438 292 264 313 413 288 347 277 302 366 356 210 243 218
235 220 59 91 76 103 84 153 133 105 111 162 151 264 213 362 220 264
BUR-N37A 75
178 159 213 218 243 292 181 223 260 242 278 240 228 245 321 267 333 313 254 220
203 167 143 158 171 142 142 141 209 151 156 151 159 145 159 176 148 164 128 152
141 101 109 126 139 176 179 123 166 162 156 126 139 139 138 175 207 142 197 157
181 144 141 111 137 72 76 172 242 192 224 187 171 199 141
BUR-N37B 75
199 156 194 213 244 294 182 230 257 232 269 230 241 261 323 271 337 299 257 220
198 164 139 163 166 151 134 144 204 148 150 152 162 145 160 171 143 169 123 149
148 97 106 117 147 183 182 122 169 157 150 125 135 139 141 175 212 139 198 153
177 139 138 113 140 69 82 168 238 191 222 187 175 199 149
BUR-N38A 61
181 243 217 232 221 177 138 146 134 158 148 131 165 203 159 175 195 188 184 218
180 198 202 182 163 143 209 187 169 143 148 190 236 199 171 173 152 129 148 128
151 124 171 97 114 107 139 67 69 156 174 174 195 165 133 230 153 119 130 55
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BUR-N38B 61
185 243 226 224 214 181 136 141 144 156 152 127 168 203 156 181 188 209 180 197
175 185 199 183 160 158 192 190 168 154 149 195 238 193 172 167 148 125 149 130
148 125 172 96 117 103 146 69 67 156 179 171 194 166 132 236 152 114 132 65
123
BUR-N39A 48
229 162 217 258 251 392 268 361 306 281 346 290 349 361 282 345 307 365 473 259
243 243 312 233 325 276 319 311 342 208 310 261 283 206 78 106 86 98 58 94
96 81 129 122 152 228 285 433
BUR-N39B 48
226 165 220 276 257 362 332 341 305 289 351 283 344 370 273 346 305 371 477 252
248 237 306 236 327 268 317 310 301 227 310 256 277 206 82 107 87 90 63 90
96 78 119 130 148 231 267 437
BUR-N40A 58
188 191 288 221 281 232 293 254 226 249 184 235 275 169 244 178 191 214 187 172
142 196 173 186 131 159 163 149 147 165 167 206 166 70 69 57 90 75 92 95
81 103 100 115 205 141 169 155 176 104 88 65 53 61 71 56 84 87
BUR-N40B 58
187 198 282 224 275 235 293 256 224 249 180 240 277 169 245 174 190 214 185 172
147 193 171 184 130 170 159 159 148 162 169 211 160 72 61 61 88 75 102 97
85 102 99 115 204 150 172 152 176 101 88 58 58 64 69 62 80 83

BUR-N42A 64
58 64 111 118 88 94 25 85 101 105 103 135 61 109 104 83 82 80 105 78
107 77 127 113 146 144 137 101 114 146 127 77 133 142 129 113 131 91 97 96
92 55 74 52 61 51 72 75 99 84 106 124 101 148 51 48 49 43 72 77
120 77 47 61
BUR-N42B 64
53 74 89 115 115 90 32 88 97 100 111 123 74 90 106 100 77 73 113 67
110 82 109 127 150 134 127 111 118 118 141 112 133 143 116 106 126 92 94 102
102 57 68 50 62 49 79 68 109 67 115 118 99 138 54 36 47 44 60 79
120 60 74 75
BUR-N43A 106
148 197 231 215 242 281 271 367 382 396 375 558 423 435 378 357 342 484 416 388
248 292 388 343 247 284 300 303 313 138 96 122 124 127 108 165 139 171 126 145
118 139 134 158 125 74 64 65 68 71 70 99 63 88 124 69 83 105 123 140
90 97 66 95 81 95 111 147 132 119 118 91 105 114 95 90 105 94 114 163
112 115 115 117 90 96 82 58 36 46 45 63 56 67 72 66 97 71 60 65
81 86 98 132 98 94
BUR-N43B 106
150 197 238 210 235 270 268 374 393 394 377 559 403 424 390 349 345 484 421 388
254 288 387 340 250 277 296 313 315 133 94 121 109 115 108 137 130 155 119 131
107 125 134 155 132 67 74 62 73 68 68 101 64 94 120 74 86 100 136 129
93 101 69 96 73 102 110 151 136 118 114 93 100 119 94 91 106 92 115 164
114 127 100 122 83 102 76 51 40 51 45 67 57 65 73 67 96 64 56 61
81 89 88 132 93 100
BUR-N44A 76
154 135 245 359 247 280 317 279 263 244 339 289 339 79 124 144 187 194 246 155
120 154 139 156 79 150 147 159 161 190 119 131 165 140 192 221 170 159 174 128
141 134 189 160 160 160 129 141 179 127 162 137 138 67 33 34 34 39 44 50
54 42 41 32 51 55 58 62 96 120 128 119 68 57 68 68
BUR-N44B 76
152 137 255 352 248 289 313 293 267 236 350 290 342 70 131 143 186 196 242 151
128 153 140 151 80 157 158 150 173 194 131 143 184 144 205 223 173 149 192 125
140 132 187 165 159 163 121 146 177 123 169 143 137 61 35 34 38 36 40 57
50 45 38 31 47 60 58 65 94 121 130 120 76 54 73 70
BUR-N45A 85
113 73 54 70 108 97 121 119 101 140 96 109 142 169 101 178 166 101 154 139
150 134 108 183 184 161 185 141 170 183 248 173 208 253 232 185 197 233 193 188
199 199 171 260 249 269 162 234 184 176 154 158 195 233 225 212 162 165 144 187
133 131 122 127 80 76 114 177 207 246 253 215 308 160 184 173 85 153 157 137
107 101 119 95 110
BUR-N45B 85
107 80 68 71 117 92 120 117 105 131 105 114 138 177 104 167 174 96 148 143
155 125 117 183 166 151 160 139 168 185 252 171 210 255 228 190 196 227 196 180
212 205 170 256 245 272 159 232 189 183 154 146 203 225 223 213 164 166 138 193
132 125 122 128 79 76 116 176 212 240 254 218 308 160 178 158 96 150 154 144
106 104 116 106 107
BUR-N46A 47
284 428 543 516 345 263 263 472 457 355 439 258 151 138 135 219 202 157 136 84
107 149 208 264 152 291 182 262 228 92 88 170 312 224 326 323 308 230 302 265
233 160 126 179 244 459 387

BUR-N46B 47
287 409 561 505 366 255 262 461 459 352 439 258 153 135 133 221 203 138 151 83
106 148 178 273 145 273 197 281 228 87 75 143 298 191 343 350 302 228 293 264
229 208 147 214 244 458 395
BUR-N47A 49
372 454 426 391 358 330 341 148 97 123 142 196 241 248 304 329 336 333 304 113
152 117 171 157 175 203 244 152 220 243 445 335 505 371 341 209 103 108 141 165
177 148 192 111 52 96 78 54 68
BUR-N47B 49
362 458 424 392 354 324 338 139 102 119 138 193 248 248 304 332 339 334 290 121
137 130 167 158 173 208 239 159 213 225 471 364 536 415 332 196 106 109 140 164
172 147 191 127 68 94 71 56 54
BUR-N48A 76
180 160 220 120 120 200 250 200 200 150 250 120 100 80 110 150 170 170 160 130
100 100 110 100 100 170 180 150 100 100 150 150 170 200 150 150 150 100 70 80
100 120 130 120 130 200 300 350 400 450 350 300 300 450 450 400 370 250 300 350
150 220 200 200 210 250 230 150 160 180 250 250 130 400 250 200
BUR-N48B 76
160 180 220 150 100 200 250 200 200 180 250 120 100 80 120 150 180 200 160 150
100 100 110 100 140 150 170 150 100 100 130 150 180 170 150 150 150 110 70 90
90 100 120 110 150 200 350 300 350 500 350 270 300 450 450 350 420 230 350 300
130 210 210 200 200 250 200 130 180 200 250 250 160 450 240 170
BUR-N49A 55
80 110 50 100 60 100 210 100 150 100 130 150 160 150 140 200 150 100 150 120
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300 200 220 190 250 200 190 220 200 200 150 250 250 200 220
BUR-N49B 55
80 110 100 90 100 90 150 150 160 100 120 150 150 150 140 200 150 120 140 100
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300 200 250 200 250 200 200 200 210 200 170 250 250 130 250
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342 426 390 319 230 222 238 191 217 185 163 179 183 146 132 148 198 196 147 98
159 184 184 212 180 189 127 156 173 130 126 139 187 106 105 156 180 136 141 122
160 134 63 69 120 131 141 148 148 128 147 95 132 105 109 177 139 147 139 97
136 153 188 179 145 134 139 135 73 79 69 105 146 113 150 181 370 349 393 440
382 333 300 408 466 318 445 228 333 355 258
BUR-N50B 91
354 414 400 326 275 222 240 191 223 183 161 173 184 137 139 151 207 190 151 87
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159 120 79 65 110 137 137 154 145 127 145 92 129 107 117 175 129 151 141 99
135 147 185 177 139 139 144 136 81 74 72 103 146 117 151 187 369 330 372 438
378 345 289 412 463 320 433 243 334 353 259
BUR-N51A 97
94 131 165 167 188 143 98 121 184 173 222 379 220 167 87 82 116 114 180 121
111 91 94 92 62 75 42 71 83 79 118 79 102 122 150 163 184 121 99 153
139 99 166 107 131 235 117 141 115 183 181 192 242 215 129 118 181 233 156 221
159 195 298 293 246 127 153 142 179 221 284 348 253 283 237 152 178 156 81 102
153 162 164 220 177 169 200 184 161 62 35 58 109 140 101 162 185

BUR-N51B 97
99 115 174 171 178 140 105 121 182 166 221 361 219 162 92 78 122 101 177 120
108 83 92 94 69 64 41 74 86 81 111 89 100 119 149 160 190 126 97 144
152 99 165 106 135 233 128 143 100 192 180 195 237 221 136 124 185 229 152 223
154 200 298 297 246 130 136 144 183 220 278 357 248 289 239 152 176 154 84 96
156 161 169 214 178 171 208 195 174 64 31 59 117 134 109 159 186
BUR-N55A 84
107 71 56 106 96 78 169 117 96 110 97 96 97 92 153 135 107 126 90 103
106 91 74 149 229 152 144 135 173 134 109 135 128 113 117 107 95 129 121 81
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119 104 93 158
BUR-N55B 84
94 77 51 107 91 82 165 112 91 127 123 120 120 105 147 141 101 133 87 117
118 91 77 152 256 161 163 158 175 127 102 113 117 116 118 109 93 129 123 87
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179 185 170 161 138 187 185 291 252 211 155 200 145 137 158 185 174 182 162 149
131 96 91 175
BUR-N56A 93
194 194 134 245 108 91 119 113 110 165 189 133 118 145 142 127 148 156 137 145
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160 122 143 113 96 40 38 34 47 76 98 95 159 151 161 230 166 119 186 96
194 188 191 129 166 166 35 35 31 31 29 27 24 24 47 71 68 75 55 56
82 78 72 82 86 90 91 120 67 61 93 82 73
BUR-N56B 93
186 202 151 224 108 99 126 111 119 175 157 137 116 149 133 127 144 156 137 134
138 60 107 86 101 84 96 98 141 88 99 148 113 102 134 73 86 86 111 142
155 127 140 111 100 40 33 37 52 73 120 107 165 139 162 224 163 120 183 127
164 189 191 132 165 163 41 32 32 33 36 25 22 26 47 72 63 79 57 53
84 73 75 82 91 85 92 119 75 57 97 80 80
BUR-N57A 84
323 259 180 164 151 152 113 129 133 159 142 142 153 128 125 143 114 93 100 142
102 89 103 125 158 122 118 100 140 85 130 114 131 132 95 89 110 101 131 141
131 115 139 126 167 117 127 117 105 61 66 95 123 93 72 105 130 144 87 78
85 76 86 103 155 146 154 193 159 149 120 102 128 165 141 135 132 192 126 84
42 38 55 48
BUR-N57B 84
330 260 173 170 153 153 109 126 140 157 143 141 152 132 124 143 118 92 103 143
98 86 103 131 156 118 117 104 142 85 128 117 124 135 93 90 109 110 128 141
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87 78 86 108 160 145 165 188 165 134 117 108 132 164 136 136 133 193 126 82
45 37 55 51
BUR-N58A 61
63 77 47 58 44 46 66 65 64 80 64 118 160 114 110 125 242 314 265 187
180 113 171 149 177 171 155 105 104 140 137 121 132 158 84 106 83 70 39 84
107 150 99 84 67 52 42 52 63 94 99 145 91 76 131 166 141 96 46 63
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BUR-N58B 62
47 52 77 40 60 33 53 56 63 53 76 68 113 164 104 114 126 226 308 257
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77 104 141 119 64 67 56 45 51 67 88 99 151 79 81 117 161 146 97 50
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

1. *Inspecting the Building and Sampling the Timbers.*

Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

2. *Measuring Ring Widths.*

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for

C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

4. Estimating the Felling Date.

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

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

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

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

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

5. Estimating the Date of Construction.

There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after

(Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences.

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

7. Ring-Width Indices.

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

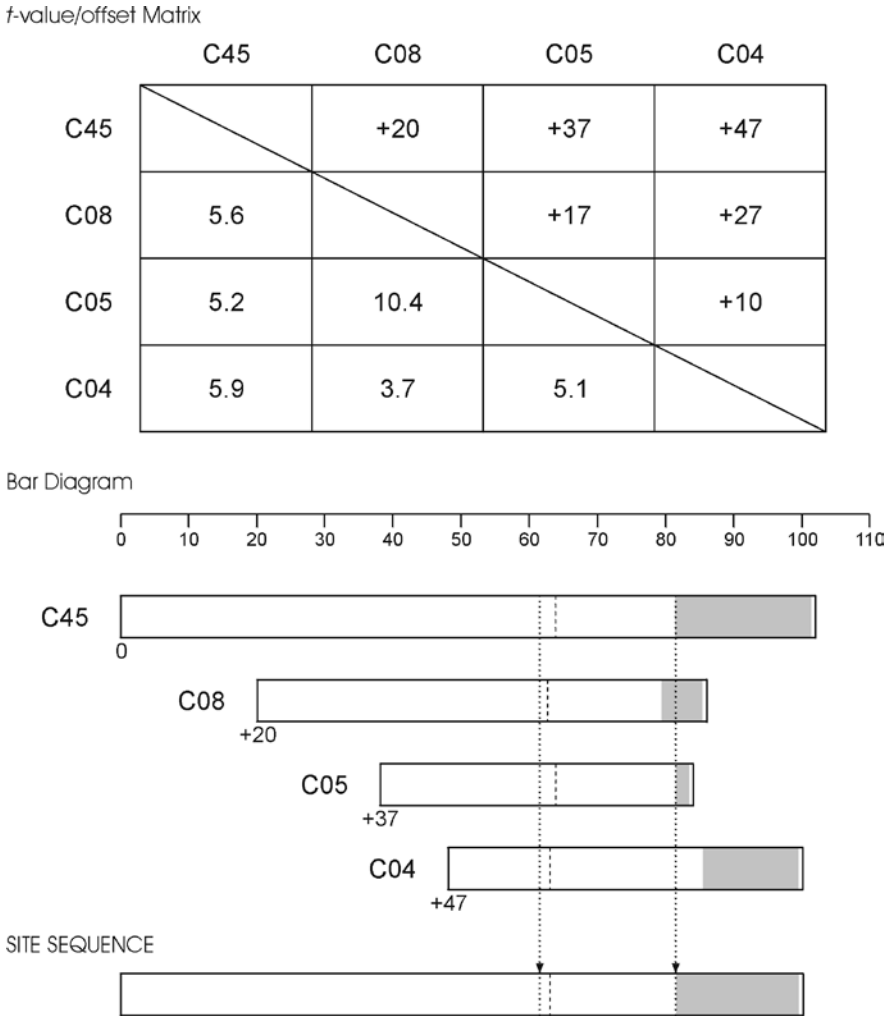


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

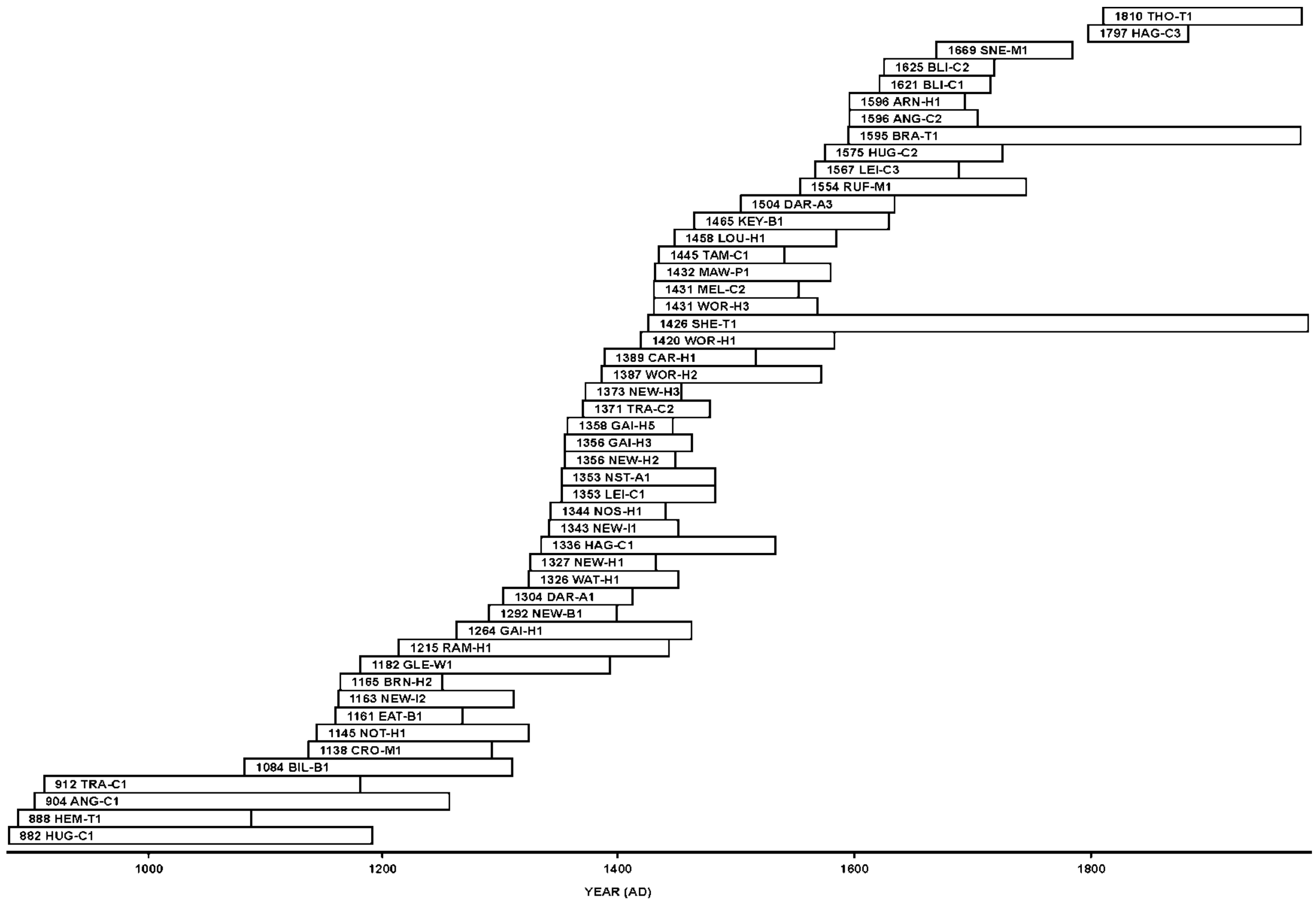
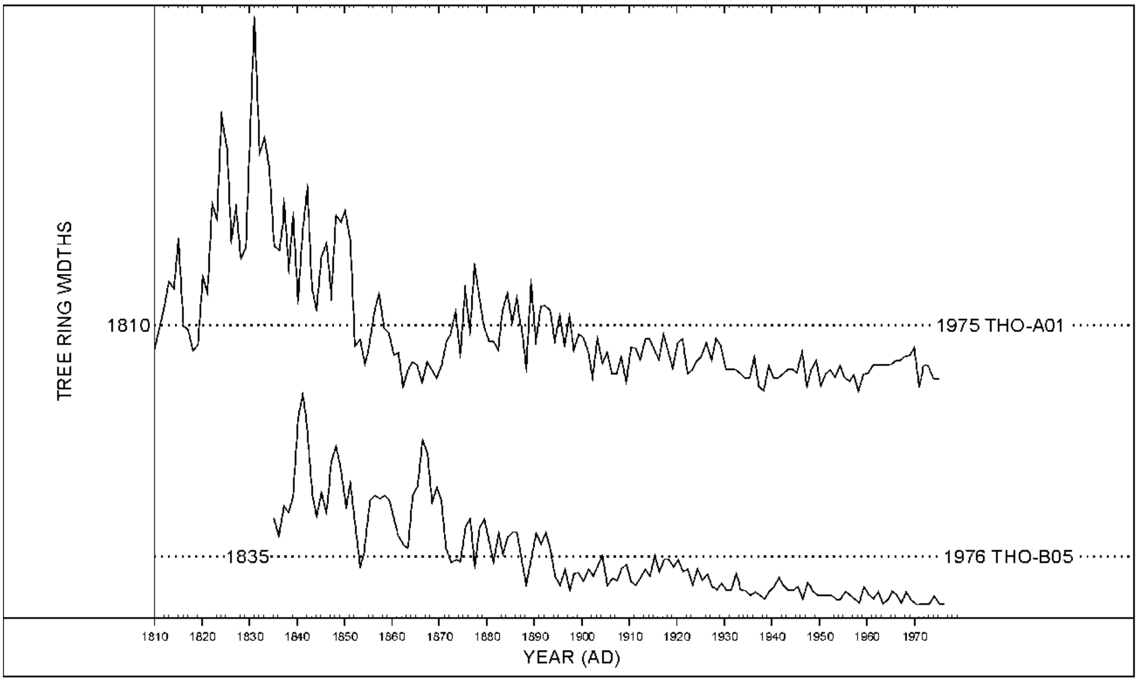


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

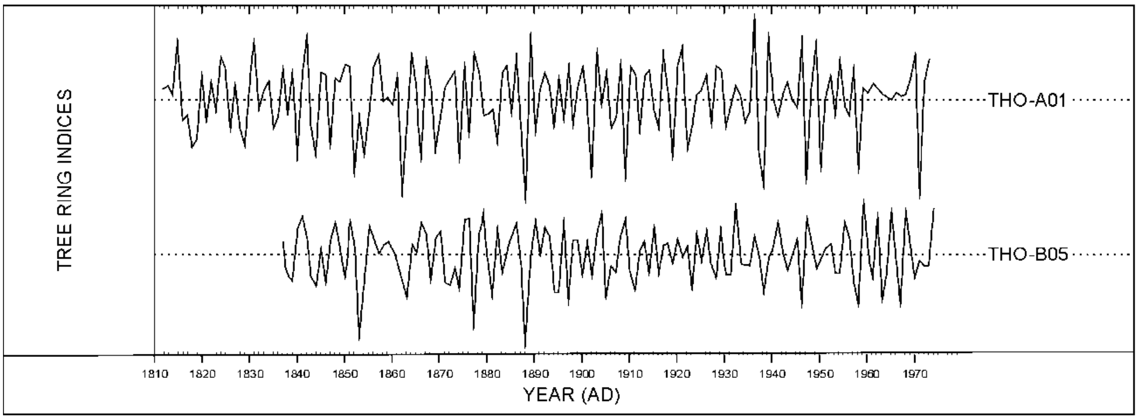


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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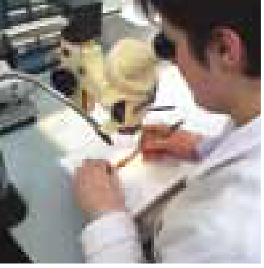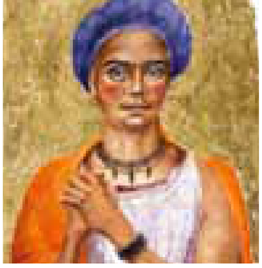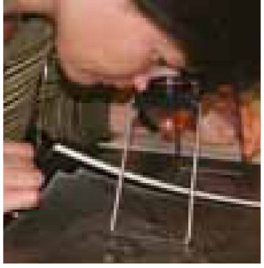

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