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AUCKLAND CASTLE, BISHOP AUCKLAND, COUNTY DURHAM
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION AND ANALYSIS

ENGLISH HERITAGE

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SUMMARY

Analysis undertaken on 64 of the 67 samples taken from various parts of this building resulted in the construction and dating of two site sequences. AUKBSQ01contains 11 samples and spans the period AD 1370–1520 and AUKBSQ02 contains 40 samples and dates to AD 1425–1698.

Timbers were identified in the roof over the Long Dining Room as being felled in AD 1520, whilst the timbers from King Charles' Room roof were felled in AD 1517–42. Two other potentially early timbers, with a *terminus post quem* for felling of AD 1482 and AD 1518 respectively, represent the extant remnants of a roof.

The Stairway roof contains timbers with signs of reuse which represent several different felling periods, timbers having been felled in AD 1515–40, AD 1642–67, and AD 1682–1707. Similarly the ceiling of the Castle Lodge cellar has timbers dated to AD 1587–1612, AD 1637–62, and AD 1658–83.

The ceiling beams in the Throne Room Undercroft were felled in AD 1651–72. The Scotland Wing roof contains timbers felled in AD 1670–95 and AD 1709–34, with the earlier of these potentially representing reused timber.

None of the samples from the Chapel could be dated.

CONTRIBUTORS

Alison Arnold and Robert Howard

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CONTENTS

INTRODUCTION

Auckland Castle, also known as Auckland Palace or the Bishop's Castle or Palace is located in the town of Bishop Auckland (Figs 1–3). It has been the official residence of the Bishop of Durham since AD 1832, although it has been owned by the diocese for more than 800 years. It was originally established as a hunting lodge for the Prince Bishops of Durham. Around the castle are 800 acres of parkland, once used by the Bishops for hunting and today open to the public.

The areas described below are those pertinent to this analysis.

Roof over the Long Dining Room

The Long Dining Room located on the first floor between the Throne Room and the King Charles Room (Fig 4) is part of the sixteenth-century additions attributed to Bishops Ruthall and Tunstall and is thought to date to *c* AD 1530. The roof above this part of the building has a very shallow pitch and consists of at least six trusses forming a single-pitch lean-to structure (Fig 5).

Roof over the King Charles' Room

Also thought to belong to this period is King Charles' Room, located immediately to the south of the Long Dining Room (Fig 4). The roof above this room contains pine trusses, thought to be eighteenth century, which sit on the remnants of an earlier oak roof. These remains consist of tiebeams and main ceiling joists (Fig 6).

Remnants of roof

A small number of redundant timbers can be seen in the north wall which separates the roofs above the Long Dining Room and the Throne Room, which are believed to be the remains of an earlier roof. From the Long Dining Room side a beam or plate aligned east-west and some other north-south beams below it can be seen (Fig 7). From the Throne Room side another east-west beam can be seen (it is unclear whether this is in fact the same beam), with north-south beams above it (Fig 8).

Roof and floor above the Stairway

The roof above the Stairway, located to the west of the Throne Room (Fig 4) is thought to be late-eighteenth century in date. It consists of principal rafter trusses with collars and purlins and can be seen to contain a number of reused oak timbers which may date to the medieval period. Additionally, the floor structure to the roof space contains a number of oak beams which also show signs of reuse (Figs 9 and 10).

Throne Room Undercroft ceiling

Beneath the Throne Room is the Undercroft, the ceiling of which contains several oak ceiling beams, some of which have redundant mortices (Fig 11). The room is thought to date to the fourteenth century.

Castle Lodge cellar ceiling

The Castle Lodge is located to the south-west of the castle itself. The ceiling of the cellar consists of a main south-north beam with east-west common joists (Fig 12). This house is thought to predate the Gatehouse which is believed to date to pre AD 1660.

Scotland Wing

The following is taken from an unpublished description written by Peter Ryder.

A narrow two-storeyed wing, long known simply as 'Scotland', extends west from the main group of buildings at Auckland Castle. It is generally thought to be of sixteenth-century date, although its north wall is exceptionally thick at ground-level and may be a remnant of something earlier. The roof structure is of 15 irregular bays; the trusses are all of basic overall form – of principal rafter construction with a single collar – but show a considerable variety in scantling and quality of timbers, reuse of members, and later modification (Fig 13). The trusses referred to are numbered from west to east (Fig 30), and the only evidence of an original carpenters' numbering scheme was the figure 'IV' on the west face of truss 6.

Trusses 1–3 all have collars halved in from the west, and carry two levels of purlins, and a diagonally-set ridge set between the overlapped ends of the principals. Truss 4 is similar but appears to have its principals lapped across the east face of the tiebeam. Truss 5 is more substantial, with its collar morticed in, and the ridge carried by the north principal, which over-rides the south. In contrast truss 6 is a cruder piece of work with slight reverse curves to its principals and a collar halved onto the west face, and the ridge carried between the overlapped ends of the blades. Truss 7 is another more substantial piece, with its collar morticed into the principals, the deep northern one of which (perhaps reused) has empty through-mortices for former butt purlins. The collar has a series of small sockets for light ceiling laths. Truss 8 is similar, except that its principals are of similar size (without the evidence for butt purlins); the collar has faint chalk writing 'Bless inn ..... of the Lord'. Truss 9 is another crude one, very like truss 6, with in-curved principals and a collar halved in from the west, whereas Truss 10 reverts to the neater form with morticed-in collar and a ridge carried on the over-riding end of the north principal. Truss 11 returns to the form of trusses 6 and 9 (although with straight blades), and a collar with a long row of sockets for ceiling joists, with below it light studding carrying a lath partition on its east face. Truss 12, set very close to truss 11, is of the

neater type, and has evidence for butt purlins again, and a unique thick collar (with joist sockets) which laps round both sides of the principals. Truss 13 is similar but with a conventional collar halved in from the west, and without earlier purlin evidence, although this is seen once more on the last truss, 14, which uniquely has its collar halved in from the east.

Chapel

This was built in the twelfth century by Bishop Hugh de le Puiset as a Banqueting Hall. It was converted to a chapel by Bishop John Cosin who arrived at Auckland in AD 1660, replacing the original chapel which had been demolished by Sir Arthur Hazlerigg after he acquired the site in AD 1646. The interior walls were raised to form the clerestory and a highly decorated panelled ceiling constructed (Fig 14). The side aisles (Fig 15) were also raised in the nineteenth century by Bishop van Mildert. The Chapel underwent a major restoration about 25 years ago which included the replacement of some of the ceiling beams.

SAMPLING

Sampling was requested by Jacqui Huntley, English Heritage, to help inform advice relating to the statement of significance being produced for the building.

Following a detailed assessment of dendrochronological potential by the authors it was agreed that sampling should be undertaken in a number of areas of the building. Thus a total of 67 timbers was sampled by coring. Each sample was given the code AUK-B (for Auckland, site 'B') and numbered 01–67. Seven of these samples are from the King Charles Room roof (AUK-B01–07), 11 from the roof above the Stairway (AUK-B08–18), 11 from the Long Dining Room roof (AUK-B19–29), four from the remains of a roof at the junction between the Long Dining Room roof and the Throne Room roof (AUK-B30–3), five from the Undercroft ceiling beams (AUK-B34–8), six from the Castle Lodge cellar ceiling (AUK-B39–44), 13 from the Scotland Wing roof (AUK-B45–57), and ten from the aisle roofs in the Chapel (AUK-B58–67). It was not possible to undertake sampling in the nave of the Chapel due to the extreme height of the timbers which made it too unsafe from a tower scaffold. Unfortunately, the position of fixed pews along the outer walls of both aisles also hindered access, thereby greatly reducing the number of timbers which could be reached. The location of samples was noted at the time of sampling and has been marked on Figures 16–39. Further details relating to the samples can be found in Table 1.

A number of other roofs were assessed for their potential suitability for tree-ring dating. These were constructed of pine but discussions led to the decision to concentrate on the oak timbers at this time. Additionally, the oak timbers of the Mural tower were found to be wide ringed with insufficient growth rings for secure dating to be viable. Access to the timbers of the 'In-fill' roof, between the Chapel and Throne Room (Fig 4) was extremely

limited (Fig 40) and although one or two timbers could be reached it was felt that due to the limited number of accessible timbers and their sporadic nature sampling would not have provided a coherent interpretation of the roof, even if dates had been gained.

ANALYSIS AND RESULTS

Three samples, two from the Remnants of roof (AUK-B32 and AUK-B33) and one from the Scotland Wing roof (AUK-B50) were found to have too few rings for secure dating and so were discarded prior to analysis. The remaining 64 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in 51 samples matching to form two groups.

Firstly, 11 samples matched each other and were combined at the relevant offset positions to form AUKBSQ01, a site sequence of 151 rings (Fig 41). This site sequence was compared with a series of relevant oak chronologies where it was found to match consistently and securely at a first-ring date of AD 1370 and a last-measured ring date of AD 1520. The evidence for this dating is given in Table 2.

Another forty samples grouped to form a second site sequence, AUKBSQ02 (Fig 42). This site sequence is of 274 rings and when compared against the reference chronologies was found to span the period AD 1425–1698. The evidence for this dating is given in Table 3.

Attempts were then made to date the remaining 13 ungrouped samples by comparing them individually against the reference chronologies but these were unsuccessful and all remain undated.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of two site sequences which together contain 51 samples. To aid interpretation samples from each area have been illustrated and discussed separately (Fig 43).

Roof over the Long Dining Room

Ten samples from this part of the building were successfully dated (three cross beams and three chocks within AUKBSQ01 and four purlins within AUKBSQ02) and appear to form a coeval group. One of these (AUK-B29) has complete sapwood and the last ring date of AD 1520, the felling date of the timber represented. A further seven of these samples have the heartwood/sapwood boundary, which in all cases are broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1499, allowing an estimated felling date to be calculated for the seven timbers

represented to within the range AD 1517–39 (allowing for sample AUK-B24 to have a last-measured ring date of AD 1516 with incomplete sapwood), consistent with these samples also having been felled in AD 1520. The remaining two dated samples (AUK-B20 and AUK-B22) have last-measured heartwood ring dates in the mid-fifteenth century making it possible that these were also felled in AD 1520.

Roof over the King Charles' Room

Seven of the timbers here have been dated (three within AUKBSQ01 and four within AUKBSQ02), again appearing to form a coeval group. Six of these have the heartwood/sapwood boundary, which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring is AD 1502 which allows an estimated felling date to be calculated for the six timbers represented to within the range AD 1517–42. The single dated sample without the heartwood/sapwood boundary (AUK-B01) has a last measured heartwood ring date which makes it possible that it was also felled in AD 1517–42.

Remnants of roof

Only two of the timbers taken from the remains of an earlier roof at the junction between the Long Dining Room and the Throne Room were dated (one within AUKBSQ01 and one in AUKBSQ02), neither of which have the heartwood/sapwood boundary ring. Sample AUK-B30 was dated to a last measured heartwood ring date of AD 1467 and AUK-B31 to a last measured heartwood ring date of AD 1503. This allows a terminus post quem for felling to be calculated for the timbers represented of AD 1482 and AD 1518 respectively.

Roof and floor above the Stairway

Eight of the timbers from this roof and two from the floor were successfully dated (one in AUKBSQ01 and nine in AUKBSQ02), only four of which have the heartwood/sapwood boundary ring. AUK-B08 and AUK-B15 (a collar and a floor beam) have similar heartwood/sapwood boundary ring dates, the average of which is AD 1500, giving an estimated felling date for the two timbers represented within the range AD 1515–40. Sample AUK-B18 (a collar) has the heartwood/sapwood boundary ring date of AD 1627, allowing an estimated felling date range to be calculated for the timber represented within the range AD 1642–67. Sample AUK-B10 (a collar) has the latest heartwood/sapwood boundary ring date of AD 1667, giving an estimated felling date for the timber represented within the range AD 1682–1707. Two (AUK-B12 and AUK-B14), a common rafter and a floor beam, of the remaining six dated samples have last measured heartwood ring dates in the later fifteenth century making it possible that they were felled in any of the three felling date ranges given above. The other four dated samples (three

common rafters and a collar) have last measured heartwood ring dates in the sixteenth century or early seventeenth century and so could have been felled in either of the two later felling date ranges. Alternatively, given that the timbers used in this part of the building show obvious signs of reuse it is possible that completely different felling/s are represented by these timbers.

Throne Room Undercroft ceiling

Five of these timbers were dated, all within site sequence AUKBSQ02. All five samples have the heartwood/sapwood boundary ring date, which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring is AD 1632, allowing an estimated felling date to be calculated for the five timbers represented to within the range AD 1651–72, allowing for the presence of a last measured ring dating to AD 1650 on AUK-B38.

Castle Lodge cellar ceiling

All six samples taken from this ceiling were successfully dated, all within AUKBSQ02. The main beam (AUK-B39) has the heartwood/sapwood boundary ring date of AD 1572, allowing an estimated felling date to be calculated for the timber represented to within the range AD 1587–1612. One of the common joists (AUK-B44) has the heartwood/sapwood boundary ring date of AD 1622, giving an estimated felling date for the timber represented of AD 1637–62. Three other common joists also have the heartwood/sapwood boundary which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date for these three samples is AD 1643, allowing an estimated felling date to be calculated for the three timbers represented to AD 1658–83. The final dated sample does not have the heartwood/sapwood boundary but with a last-measured heartwood ring date of AD 1600 it is possible it was felled in either AD 1637–62 or AD 1658–83.

Scotland Wing

Eleven of the samples from this roof were successfully dated, all within AUKBSQ02. Five of these have the heartwood/sapwood boundary ring date, one of which is substantially earlier than the other four. Sample AUK-B53 has the heartwood/sapwood boundary ring date of AD 1655, allowing an estimated felling date to be calculated for the timber represented to within the range AD 1670–95. The other four samples have similar heartwood/sapwood boundary ring dates which are suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1694, allowing an estimated felling date range to be calculated for the four timbers represented of AD 1709–34. The other six dated samples do not have the heartwood/sapwood boundary ring date but with last-measured heartwood ring dates ranging from AD 1589 (AUK-B55) to AD 1653 (AUK-

B56) these timbers could have been felled either in AD 1670–95 or AD 1709–34, or indeed in a separate felling/s altogether. It can be said though that one of these samples (AUK-B56) does match AUK-B53 at the value of t =7.4 which might lend further support to this sample also having a felling date of AD 1670–95.

All felling date ranges have been calculated using the estimate that mature oak trees in this area have between 15 and 40 sapwood rings.

DISCUSSION

Prior to tree-ring analysis being undertaken the Long Dining Room (and presumably the roof above it) was thought to date to *c* AD 1530. The King Charles Room was believed to date to the same period, and although much of the roof above this room had obviously been replaced in pine in the eighteenth century, these new trusses sit on oak beams, thought to be the remains of an earlier roof. Remains of another redundant roof are seen in the wall between the Long Dining Room and Throne Room roofs but it was unclear exactly when these timbers might date to. Although the Chapel building itself is thought to date to the twelfth century, the roofs were believed to be seventeenth century, although they were also known to have undergone further work in the nineteenth and twentieth centuries. The Castle Lodge was thought to be pre AD 1660 whilst the roof above the Stairway is believed to be eighteenth century but clearly contains reused timber, as does the floor there. Also thought to be eighteenth century is the roof of the Scotland Wing, although the wing itself is thought to be sixteenth century.

The earliest dates obtained are from the roofs above the Long Dining Room and the King Charles Room. Timbers from the Long Dining Room roof are now known to have been felled in AD 1520, with construction believed to have followed shortly after. The oak beams upon which the pine trusses of the roof above the King Charles Room sit, thought to be the remains of an earlier roof have been dated to AD 1517–42, a date which suggests survival of historic beams associated with the construction of the room beneath. These dates support and strengthen those attributed to these parts of the castle from documentary sources.

Also potentially early, are the redundant timbers in the wall between the roofs above the Long Dining Room and the Throne Room. Two of these have been dated, one to a terminus post quem for felling of AD 1482 and one to a *terminus post quem* for felling of AD 1518.

The roof and attic floor above the Stairway can be seen to contain a large number of reused timbers. At least two of these timbers are now known to have been felled in AD 1515–40, one in AD 1642–67, and one in AD 1682–1707. Of the remaining dated timbers from this roof, two could have been felled in any of these date ranges with the other four possibly being felled in either of the later two ranges. Alternatively, given that the roof and floor are obviously constructed from timber of various dates it is possible that additional felling/s are represented within the timbers.

The Castle Lodge cellar ceiling also contains timbers representing several different phases of felling. The main beam was felled in AD 1587–1612, whereas one of the common joists dates to AD 1637–62, and a further three timbers to AD 1658–83. This may mean that the main beam was salvaged from a previous structure when the ceiling was constructed in the mid-seventeenth century or that the ceiling was constructed in AD 1587–1612 and renewed or repaired later in the seventeenth century in the form of replacement joists. Given that this building is believed to be pre AD 1660 it seems most likely that the latter explanation is the correct one.

Timber belonging to the third quarter of the seventeenth century was found within the Throne Room Undercroft ceiling. Here a number of beams were dated to AD 1651–72. It is not clear whether these beams are reused, something further study may clarify, and so whether this dates the construction of the ceiling or simply of the timbers. It is possible that these timbers relate to the substantial renovation works undertaken by Bishop Cosin (AD 1660–72)

The latest material identified was within the roof of the Scotland Wing. Here one beam was dated to AD 1670–95 and a further four to AD 1709– 34. The earlier date was gained for the north principal of truss 7 which Peter Ryder had suggested might be reused. The dates gained do seem to support this, suggesting construction occurred in the first half of the eighteenth century and incorporated at least one earlier timber.

It is unfortunate that no timber was dated from the Chapel. However, given the limited number of accessible timbers and the fact that from a visual inspection it could be seen that the timber appeared to be of various different phases it is perhaps not surprising that no sample matching occurred. With the longest Chapel sample being only 68 rings, it is also unsurprising that it was not possible to successfully date any individual samples either.

Amongst the samples we have at least one, and a few possible 'same tree' matches. In all cases these high matches are between samples from the same areas. Samples AUK-B06 and AUK-B07, both from the roof above the King Charles Room, match each other at a value of t=24.2 with the next 'best' match being between AUK-B36 and AUK-B37 (both Undercroft ceiling samples) matching at t=13.3.

It can be seen that both AUKBSQ01 and AUKBSQ02 match most highly against reference chronologies from the north-east (Tables 2 and 3) and yet they do not match against each other, despite having overlapping date spans. This suggests the use of at least two separate woodland sources for the timber, perhaps not unexpected given the size of the building. Furthermore, it can be seen that the Long Dining Room, the King Charles' Room, the roof Remnants, and above the Stairway contain some timbers in AUKBSQ01 and some in AUKBSQ02, suggesting individual phases contain timbers of separate sources. It may be that the timber element (or even who was undertaking that task) determined which source was used. Amongst the King Charles' Room samples those taken from cross-beams are in AUKBSQ01 and those from tiebeams and wall plates are in

AUKBSQ02 and the amongst the dated Long Dining Room samples, cross beams and chocks are in AUKBSQ01 and purlins in AUKBSQ02.

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TABLES

Table 1: Details of tree-ring samples from Auckland Castle

Sample Number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof over the King Charles' Room						
AUK-B01	Mid cross beam	83	--	1370	----	1452
AUK-B02	North cross beam	110	h/s	1389	1498	1498
AUK-B03	South cross beam	98	h/s	1407	1504	1504
AUK-B04	South tiebeam	64	h/s	1437	1500	1500
AUK-B05	North tiebeam	64	h/s	1441	1504	1504
AUK-B06	North wallplate	67	h/s	1438	1504	1504
AUK-B07	South wallplate	68	h/s	1437	1504	1504
Roof and floor above the Stairway – reused						
AUK-B08	Collar, truss 2	65	h/s	1434	1498	1498
AUK-B09	South common rafter 3, bay 2	90	--	1447	----	1536
AUK-B10	Collar, truss 1	113	h/s	1555	1667	1667
AUK-B11	South common rafter 1, bay 3	136	--	1480	----	1615
AUK-B12	South common rafter 4, bay 3	54	--	1441	----	1494
AUK-B13	South common rafter 3, bay 3	95	--	1454	----	1548
AUK-B14	Attic floor beam (south), bay 3	51	--	1425	----	1475
AUK-B15	Attic floor beam (north), bay 3	69	h/s	1434	1502	1502
AUK-B16	Collar, truss 3	83	--	1470	----	1552
AUK-B17	Attic floor beam (north), bay 4	108	--	----	----	----
AUK-B18	Collar, truss 4	141	h/s	1487	1627	1627
Roof over the Long Dining Room						
AUK-B19	Cross beam, 2-3	107	h/s	1399	1505	1505
AUK-B20	Cross beam, 3-4	94	--	1376	----	1469
AUK-B21	Purlin, truss 3-4	78	h/s	1428	1505	1505
AUK-B22	Chock 2	84	--	1375	----	1458
AUK-B23	Mid chock 4	99	h/s	1402	1500	1500
AUK-B24	Chock 8	130	22	1387	1494	1516
AUK-B25	Lower purlin, 3-4	63	05	1444	1501	1506
AUK-B26	Upper purlin, 4-5	71	h/s	1430	1500	1500
AUK-B27	Cross beam, 5-6	67	--	----	----	----
AUK-B28	Upper purlin, 6-7	64	07	1431	1487	1494
AUK-B29	Cross beam, 8-9	124	36C	1397	1484	1520
Remnants of roof						
(accessed from Long Dining Room roof)						
AUK-B30	East-west plate	78	--	1390	----	1467
(accessed from Throne Room roof)						
AUK-B31	North-south beam (west)	58	--	1446	----	1503
AUK-B32	North-south beam (east)	NM	--	----	----	----
AUK-B33	East-west plate plate	NM	--	----	----	----
Throne Room Undercroft ceiling						
AUK-B34	East-west beam	134	h/s	1495	1628	1628
AUK-B35	N-S beam 1 (from east)	202	02	1435	1634	1636
AUK-B36	N-S beam 2 (from east)	134	h/s	1496	1629	1629
AUK-B37	N-S beam 4 (from east)	140	h/s	1494	1633	1633
AUK-B38	N-S beam 2 (north of E-W beam)	118	12	1533	1638	1650
Castle Lodge, cellar ceiling						
AUK-B39	Main beam	144	h/s	1429	1572	1572
AUK-B40	Joist 3 (west)	155	h/s	1484	1638	1638
AUK-B41	Joist 1 (west)	182	15	1475	1641	1656
AUK-B42	Joist 6 (west)	117	04	1537	1649	1653
AUK-B43	Joist 5 (east)	126	--	1475	----	1600
AUK-B44	Joist 6 (east)	146	02	1479	1622	1624
Scotland Wing roof						
AUK-B45	South principal rafter, truss 6	100	h/s	1599	1698	1698
AUK-B46	North principal rafter, truss 6	96	h/s	1600	1695	1695
AUK-B47	North principal rafter, truss 7	90	--	1544	----	1633
AUK-B48	Collar, truss 11	86	h/s	----	----	----
AUK-B49	North principal rafter, truss 11	102	h/s	1588	1689	1689
AUK-B50	Collar, truss 10	NM	--	----	----	----
AUK-B51	Collar, truss 2	113	--	1500	----	1612
AUK-B52	North principal rafter, truss 3	164	--	1448	----	1611
AUK-B53	Collar, truss 5	80	01	1577	1655	1656
AUK-B54	South principal rafter, truss 7	81	--	1543	----	1623
AUK-B55	North principal rafter, truss 8	151	--	1439	----	1589
AUK-B56	Collar, truss 8	105	--	1549	----	1653
AUK-B57	South principal rafter, truss 11	70	h/s	1624	1693	1693
Chapel						
South aisle						
AUK-B58	South common rafter 2, bay 2	65	h/s	----	----	----
AUK-B59	Tiebeam, truss 3	57	01	----	----	----
AUK-B60	Ridge beam, bay 3	58	--	----	----	----
AUK-B61	Tiebeam, truss 4	58	--	----	----	----
AUK-B62	Tiebeam, truss 6	57	05	----	----	----
AUK-B63	South common rafter 4, bay 5	65	03	----	----	----
North aisle						
AUK-B64	North common rafter 4, bay 2	68	h/s	----	----	----
AUK-B65	Tiebeam, truss 5	61	h/s	----	----	----
AUK-B66	North common rafter 2, bay 8	57	04	----	----	----
AUK-B67	Tiebeam, truss 9	59	h/s	----	----	----

*NM = not measured

**h/s = the heartwood/sapwood boundary 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 AUKBSQ01 and relevant reference chronologies when the first ring date is AD 1370 and the last-ring date is AD 1520

Reference chronology	*t*-value	Span of chronology	Reference
Witton Hall Farm, Witton Gilbert, County Durham	8.6	AD 1342–1441	Howard *et al* 1996
Hunwick Hall Farm, Hunwick, County Durham	8.0	AD 1402–1497	Arnold *et al* 2004a
Headlands Hall, Liversedge, West Yorkshire	7.9	AD 1388–1487	Tyers 2001
Low Harperley Farmhouse, Wolsingham, County Durham	7.7	AD 1356–1604	Arnold *et al* 2006a
35 The Close, Newcastle upon Tyne, Tyne and Wear	7.4	AD 1365–1513	Howard *et al* 1991
Thatched Cottage, Hill Wootton, Warwicks	7.3	AD 1392–1469	Alcock *et al* 1989
Easington, County Durham	7.1	AD 1375–1489	Arnold *et al* 2008

Table 3: Results of the cross-matching of site sequence AUKBSQ02 and relevant reference chronologies when the first-ring date is AD 1425 and the last-measured ring date is AD 1698

Reference chronology	*t*-value	Span of chronology	Reference
Low Harperley Farmhouse, Wolsingham, County Durham	15.0	AD 1356–1604	Arnold *et al* 2006a
Dilston Castle, Corbridge, Northumberland	14.1	AD 1402–1611	Arnold *et al* 2003
Hallgarth Pittington, County Durham	13.3	AD 1336–1624	Howard *et al* 2002
Durham Cathedral (refectory roof), County Durham	12.5	AD 1431–1683	Arnold *et al* 2007
Moot Hall, Hexham, Northumberland	11.7	AD 1341–1539	Arnold *et al* 2004b
Midridge Grange, Heighington, Durham	11.4	AD 1427–1516	Arnold *et al* 2006b
Bull Hole Byre, Bearpark, Durham	11.2	AD 1452–1620	Arnold *et al* 2002

FIGURES

Figure 1: Map to show the general location of Bishop Auckland, circled © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: Map to show the location of Bishop Auckland, circled © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

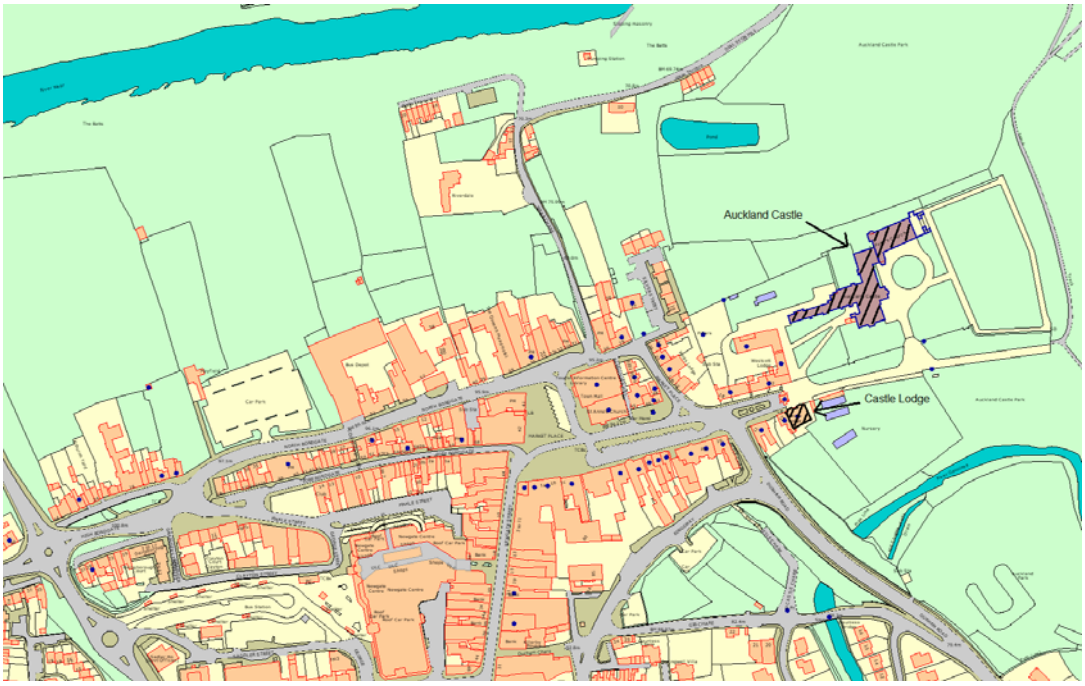

Figure 3: Map to show the location of Auckland Castle and Castle Lodge, arrowed © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

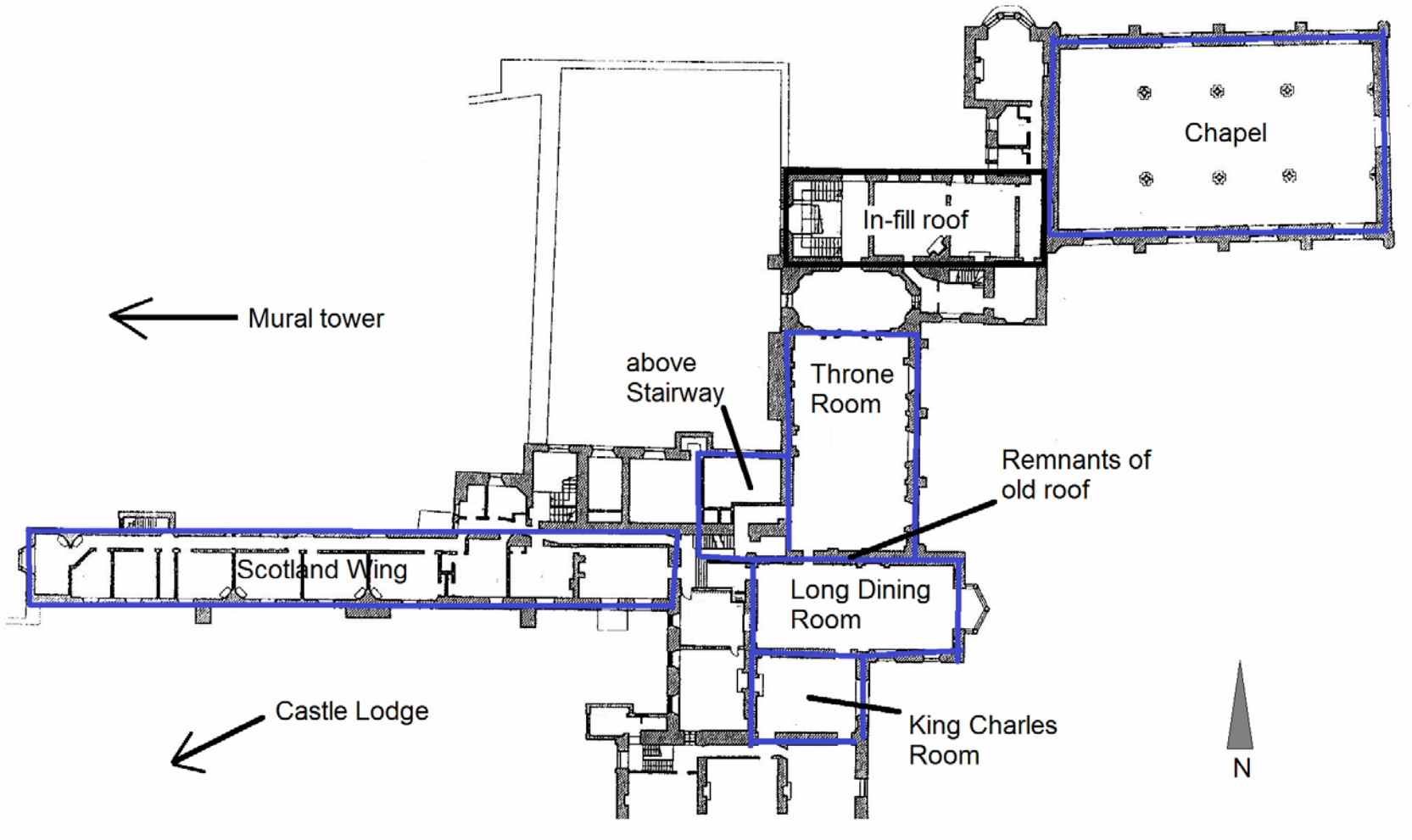

Figure 4: Plan of Auckland Castle, with those areas under investigation outlined in blue (Smithsgore Architects)

Figure 5: Roof over Long Dining Room, looking west (Alison Arnold)

Figure 6: Roof over the King Charles Room, looking east (Alison Arnold)

Figure 7: Photograph showing the east-west beam in the wall between this roof (above the Long Dining Room) and the one over the Throne Room, looking north (Alison Arnold)

Figure 8: Photograph showing the beams in the wall between this roof (above the Throne Room) and the Long Dining Room, looking south (Alison Arnold)

Figure 9: Principal rafter roof over the Stairway; the floor structure contains a number of re-used oak timbers, looking west (Alison Arnold)

Figure 10: The roof above the Stairway, one of the reused timbers (Alison Arnold)

Figure 11: Throne Room Undercroft ceiling, looking north (Alison Arnold)

Figure 12: Gate Lodge cellar ceiling, looking south-west (Alison Arnold)

Figure 13: Scotland wing roof, looking west (Alison Arnold)

Figure 14: Chapel; nave ceiling (Alison Arnold)

Figure 15: Chapel; north aisle, looking east (Alison Arnold)

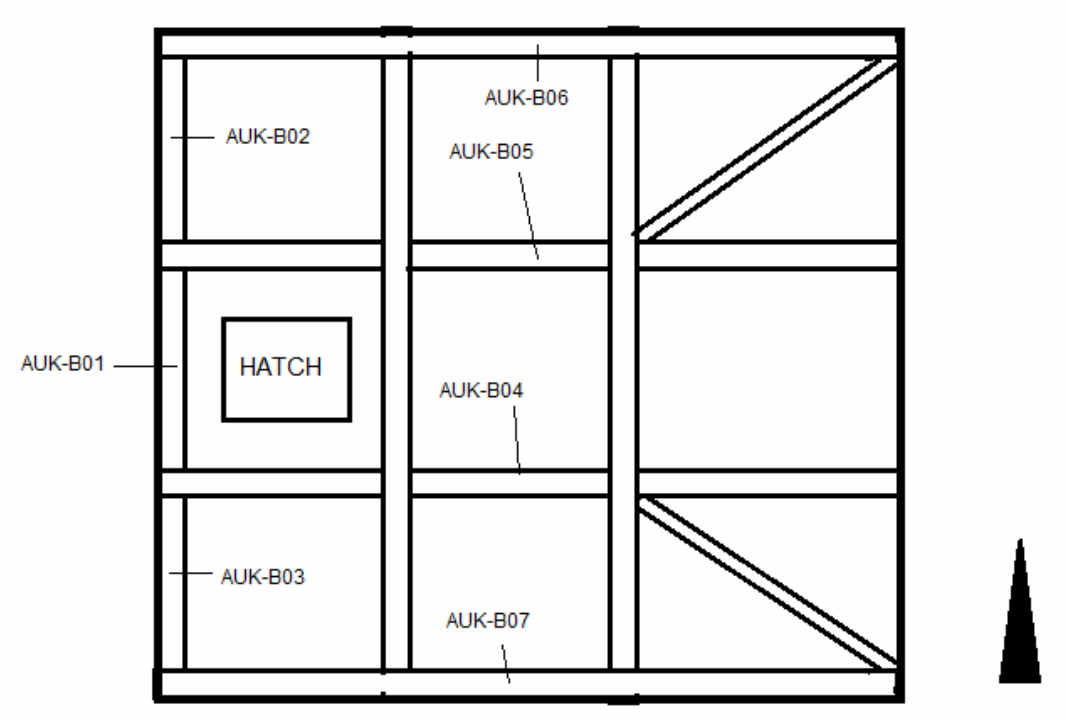

Figure 16: Sketch plan of the roof above the King Charles Room to show the location of samples AUK-B01–07

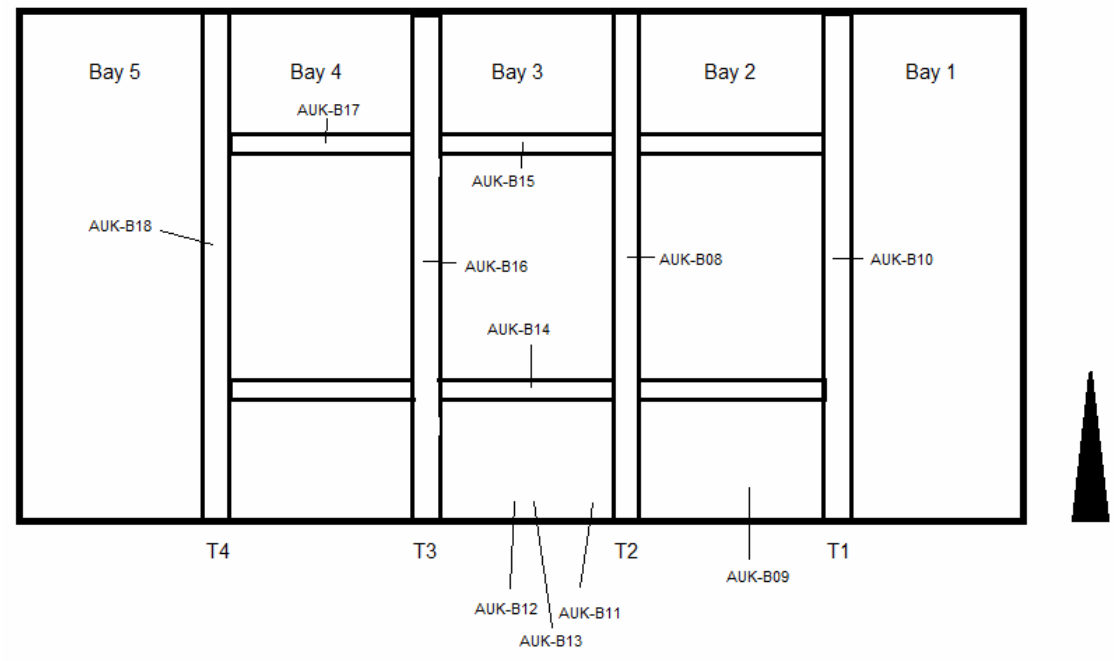

Figure 17: Sketch plan of the roof above the Stairway, showing the location of samples AUK-B08–18

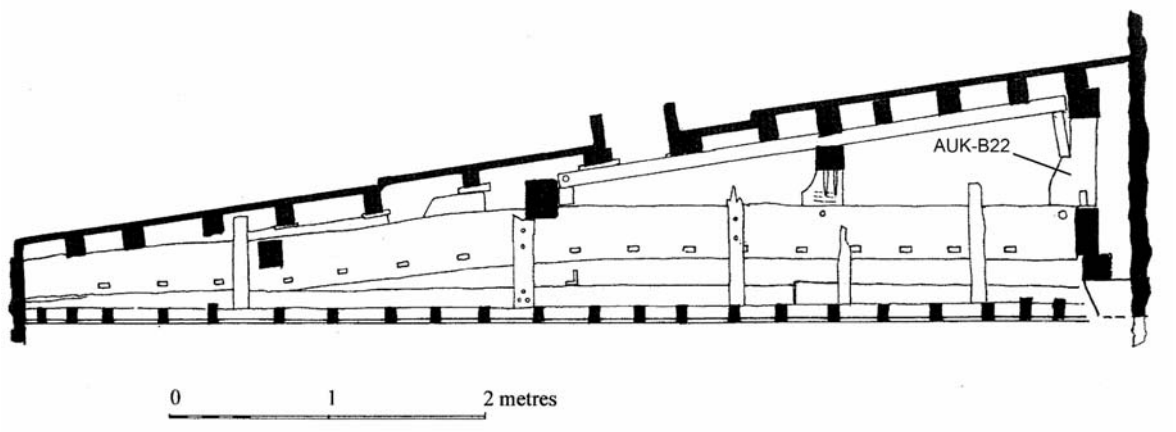

Figure 18: Roof over Long Dining room, truss 2 (east face), showing the location of sample AUK-B22 (Peter Ryder)

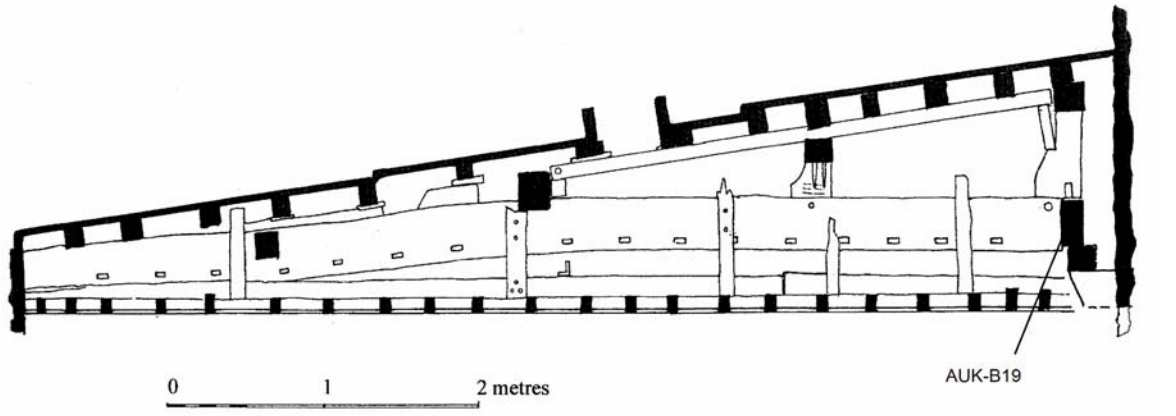

Figure 19: Roof over Long Dining room, truss 3 (east face), showing the location of sample AUK-B19 (Peter Ryder)

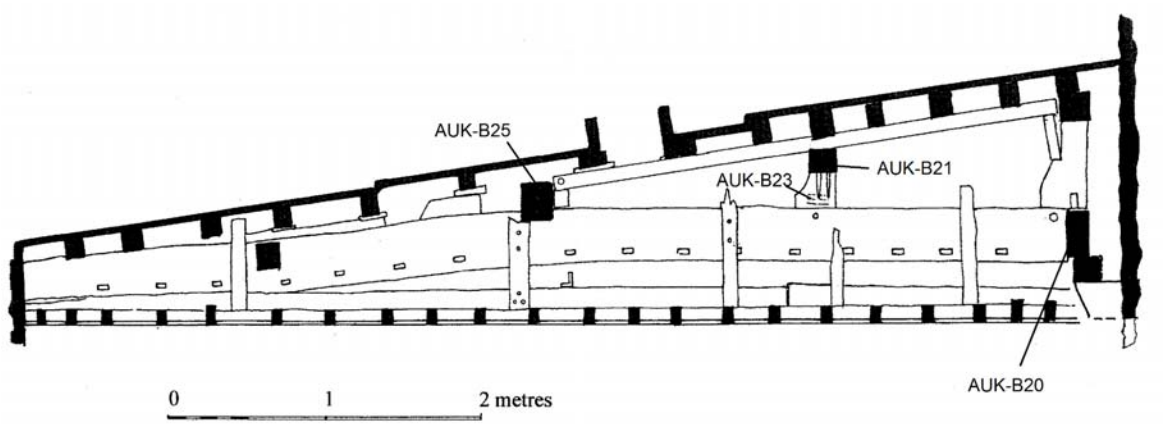

Figure 20: Roof over Long Dining room, truss 4 (east face), showing the location of samples AUK-B20–1, AUK-B23, and AUK-B25 (Peter Ryder)

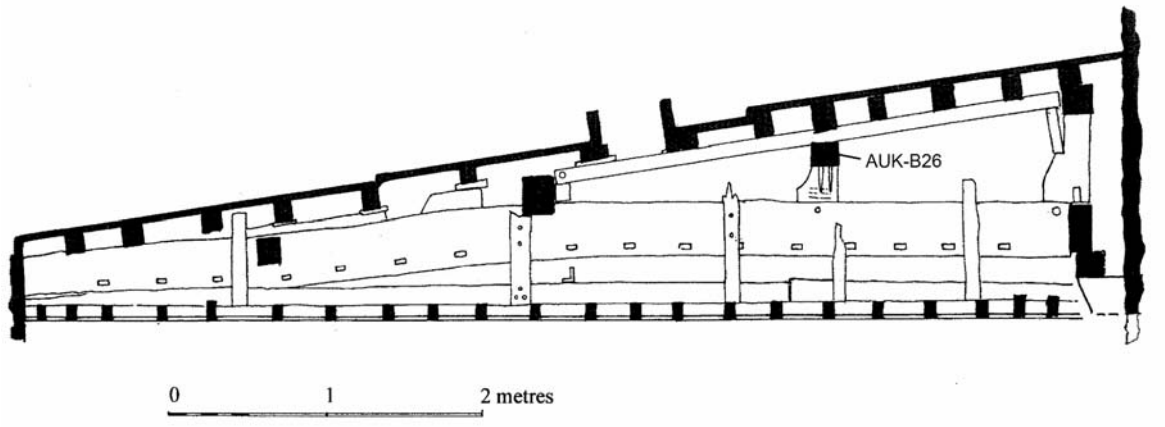

Figure 21: Roof over Long Dining room, truss 5 (east face), showing the location of sample AUK-B26 (Peter Ryder)

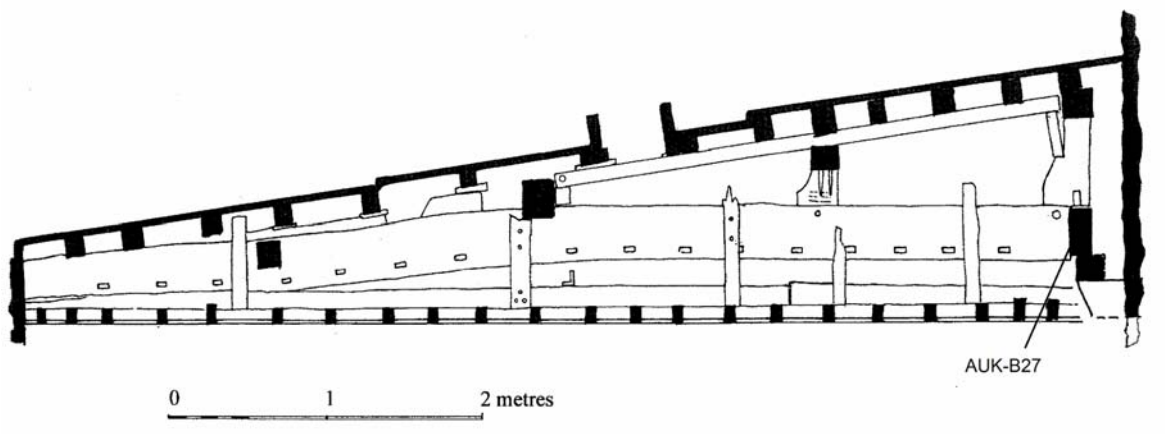

Figure 22: Roof over Long Dining room, truss 6 (east face), showing the location of sample AUK-B27 (Peter Ryder)

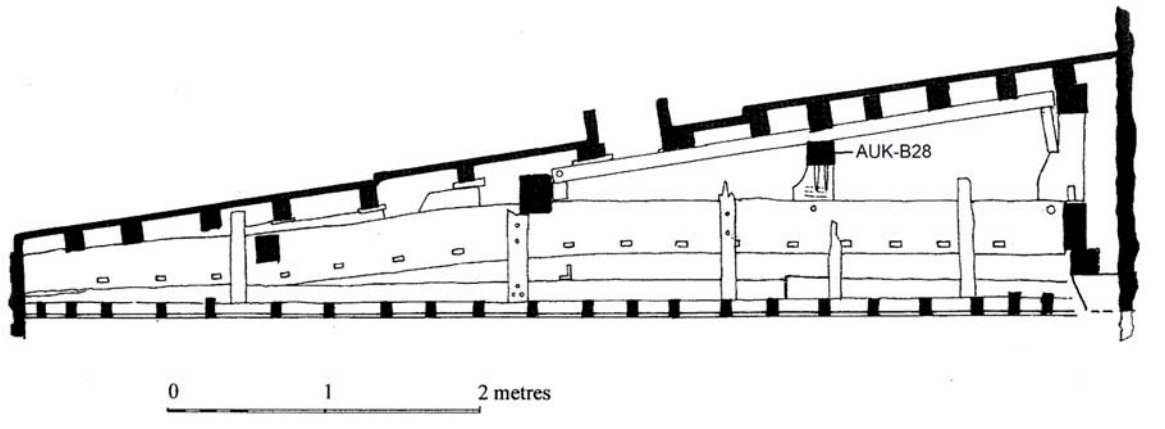

Figure 23: Roof over Long Dining room, truss 7 (east face), showing the location of sample AUK-B28 (Peter Ryder)

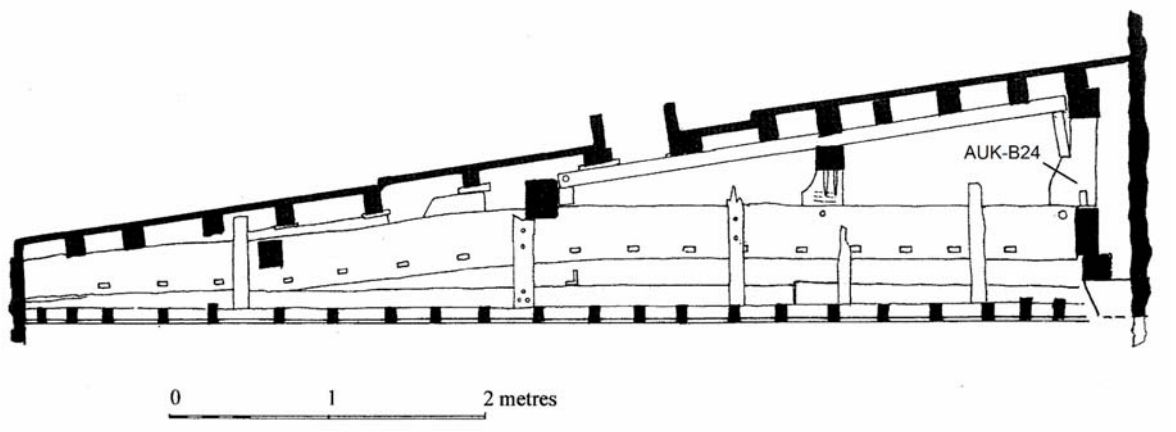

Figure 24: Roof over Long Dining room, truss 8 (east face), showing the location of sample AUK-B24 (Peter Ryder)

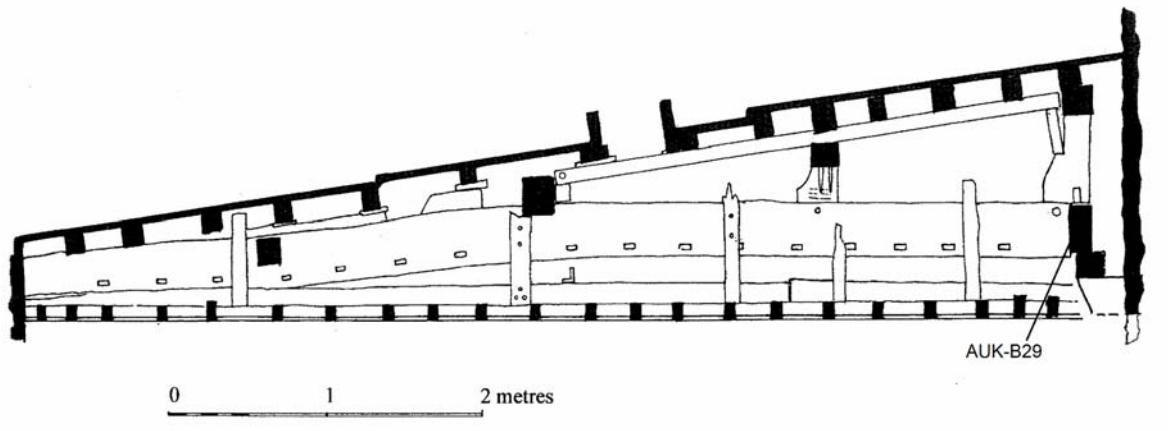

Figure 25: Roof over Long Dining room, truss 9 (east face), showing the location of sample AUK-B29 (Peter Ryder)

Figure 26: Photograph taken from the roof above the Long Dining Room, showing the location of sample AUK-B30

Figure 27: Photograph taken from the roof above the Throne Room, showing the location of samples AUK-B31–3

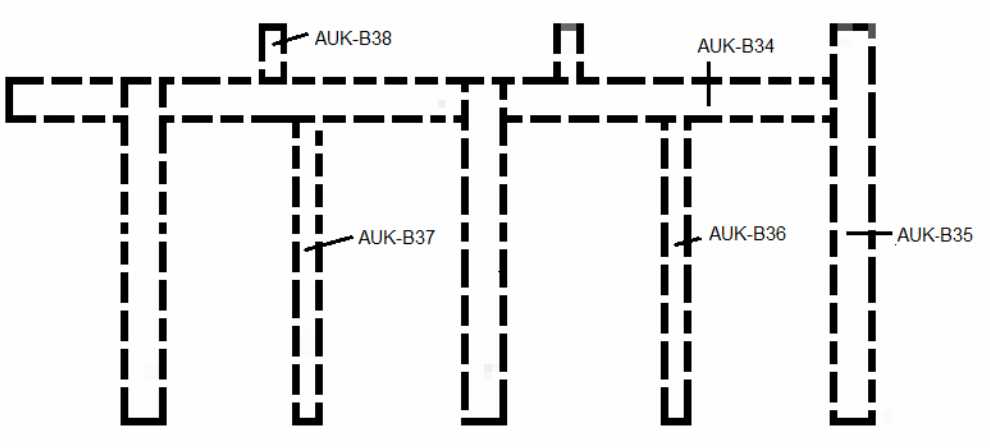

Figure 28: Sketch plan of the Throne Room Undercroft ceiling, showing the location of samples AUK-B34–8

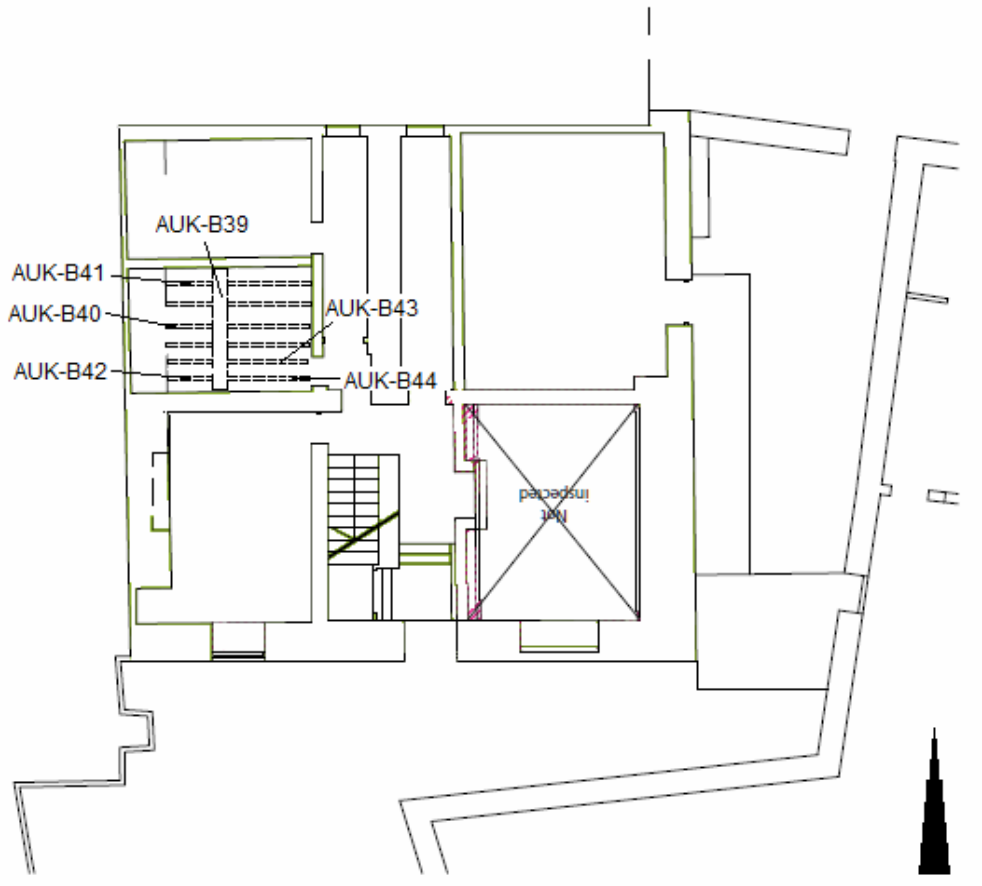

Figure 29: Castle Lodge, basement plan, showing the location of samples AUK-B39–44 (after Alan Baxter & Associates)

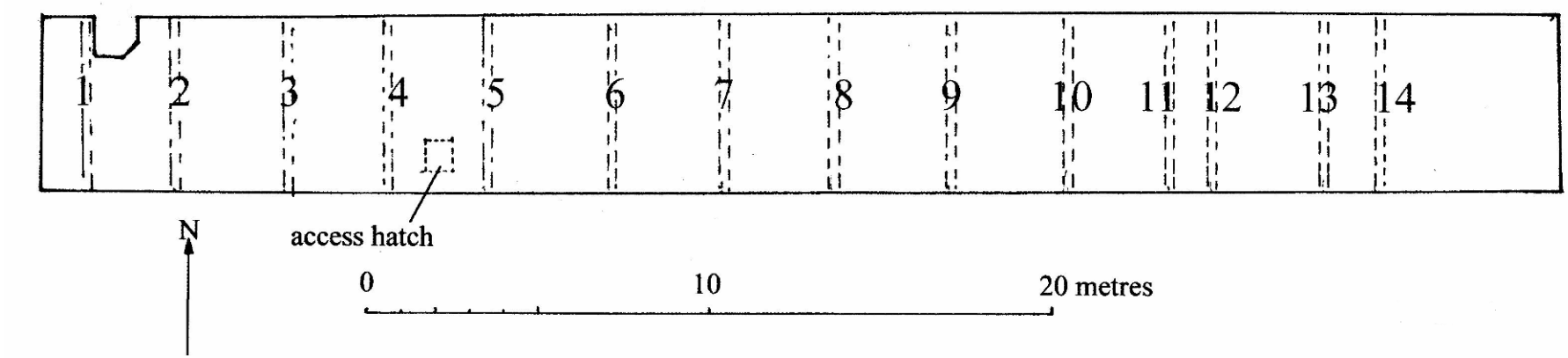

Figure 30: Plan of the Scotland Wing, showing location of trusses (Peter Ryder)

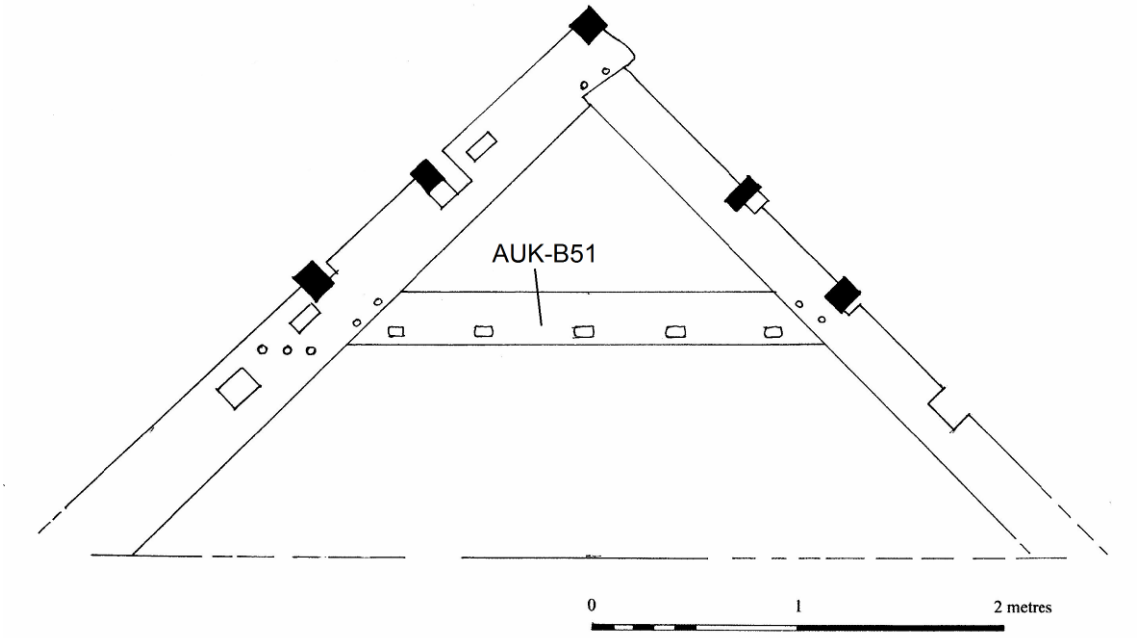

Figure 31: Scotland Wing, truss 2 (west face), showing the location of sample AUK-B51 (Peter Ryder)

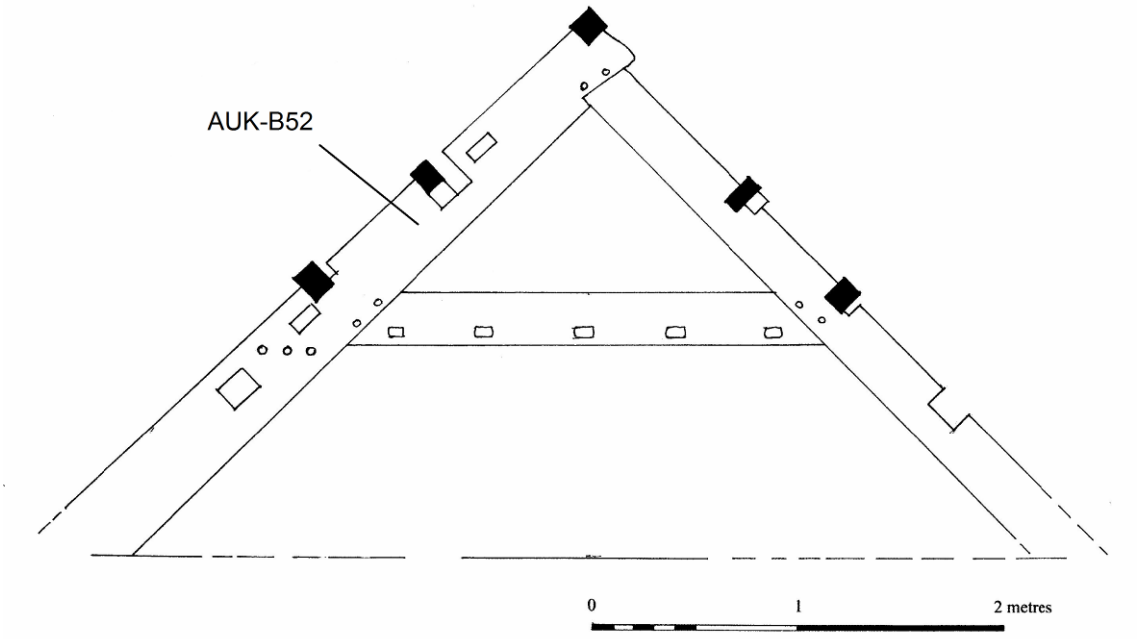

Figure 32: Scotland Wing, truss 3 (west face), showing the location of sample AUK-B52 (Peter Ryder)

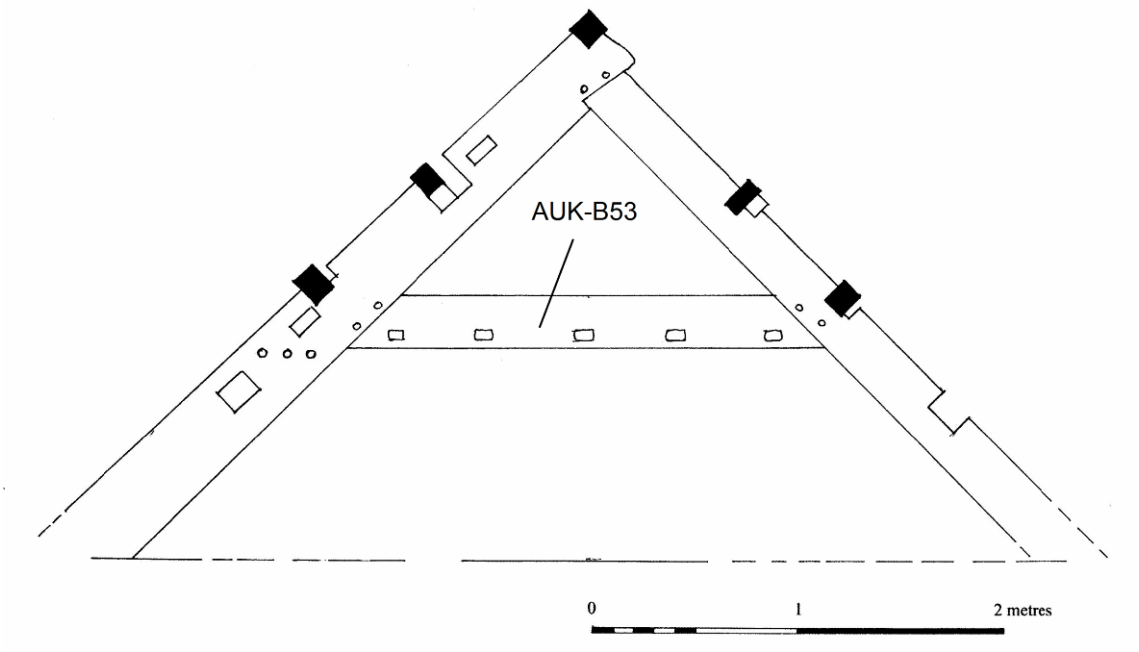

Figure 33: Scotland Wing, truss 5 (west face), showing the location of sample AUK-B53 (Peter Ryder)

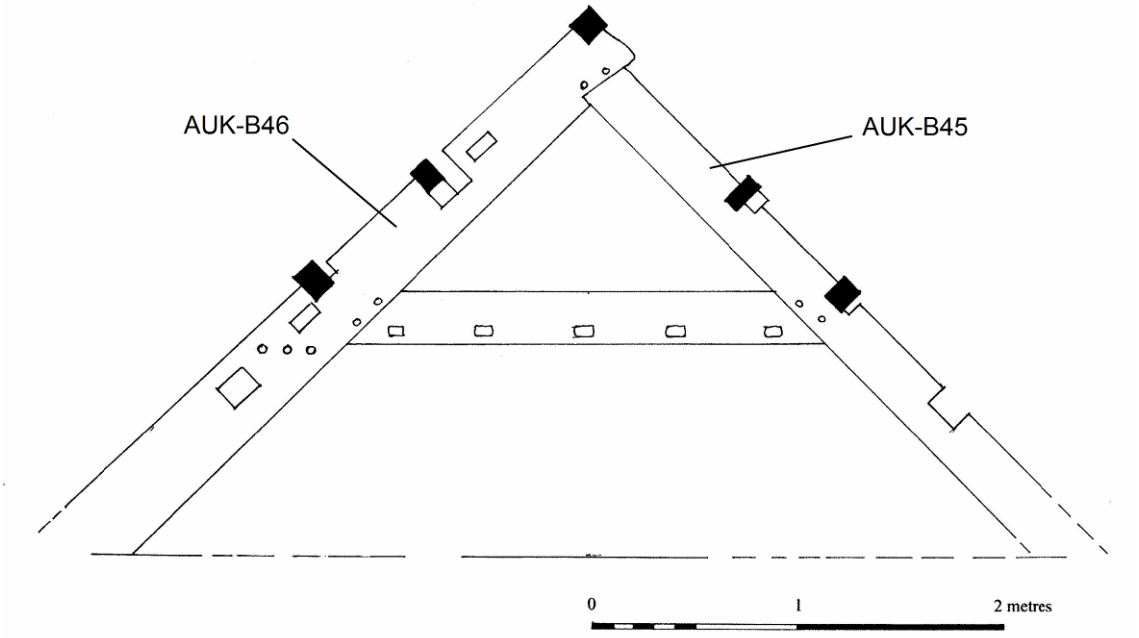

Figure 34: Scotland Wing, truss 6, showing the location of samples AUK-B45 and AUK-B46 (Peter Ryder)

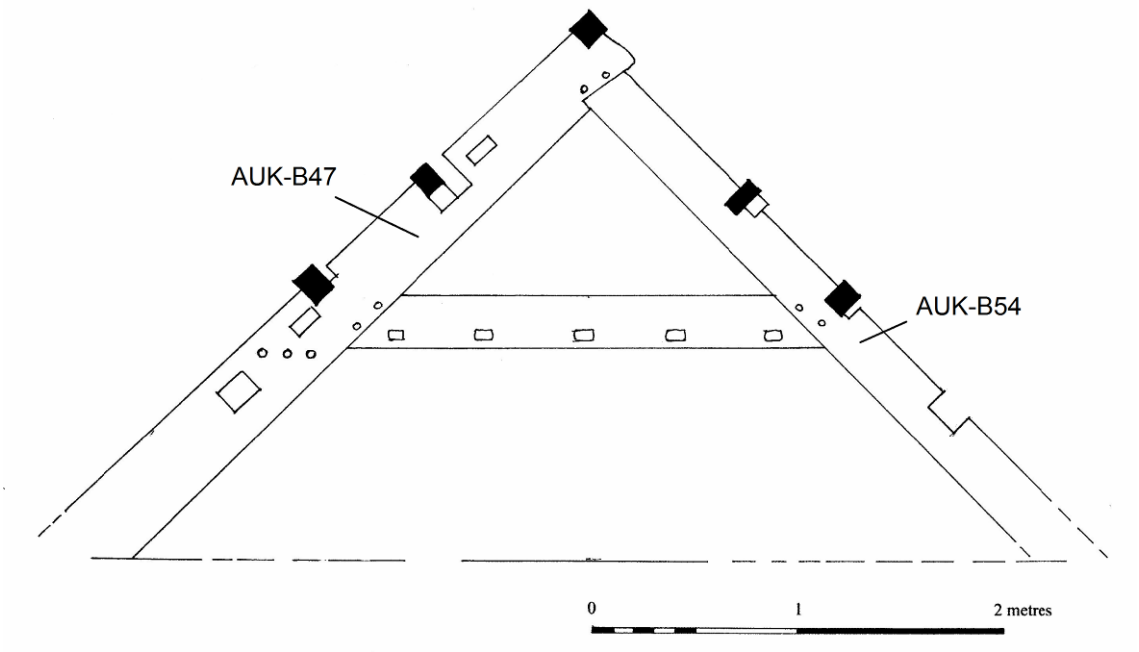

Figure 35: Scotland wing, truss 7 (west face), showing the location of samples AUK-B47 and AUK-B54 (Peter Ryder)

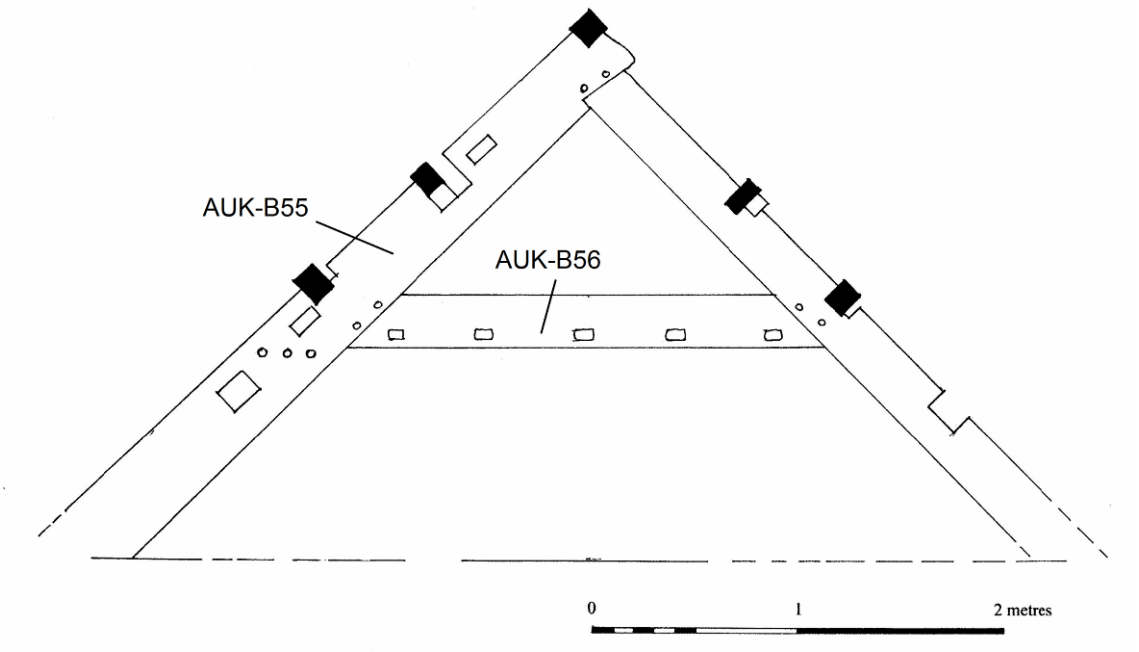

Figure 36: Scotland Wing, truss 8 (west face), showing the location of samples AUK-B55 and AUK-B56 (Peter Ryder)

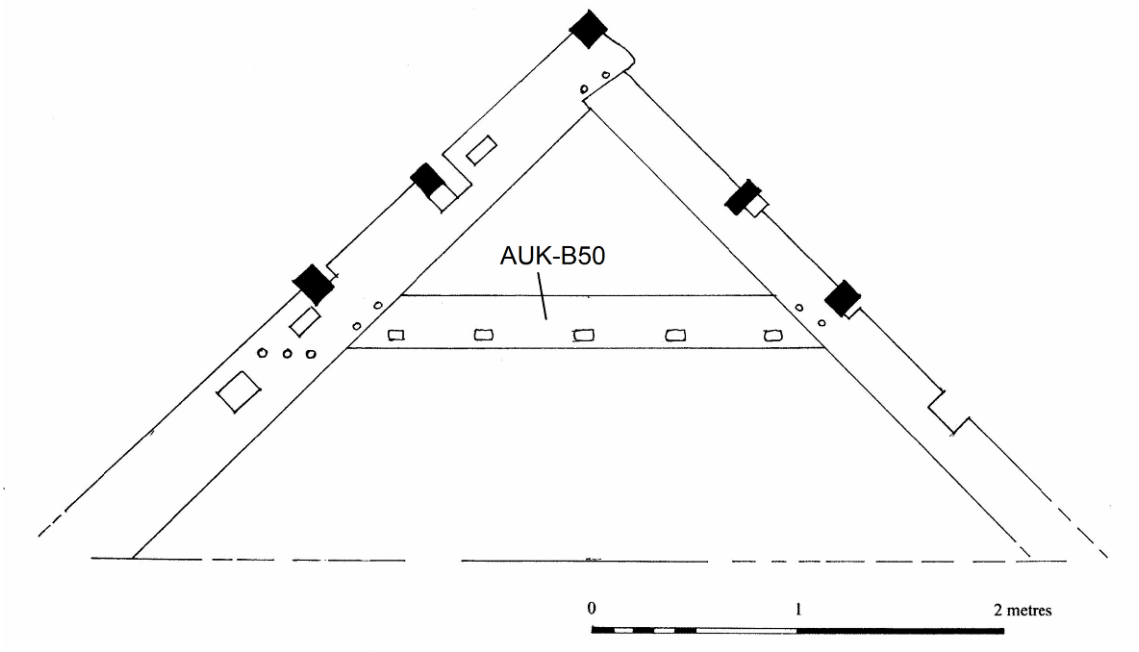

Figure 37: Scotland Wing, truss 10 (west face), showing the location of sample AUK-B50 (Peter Ryder)

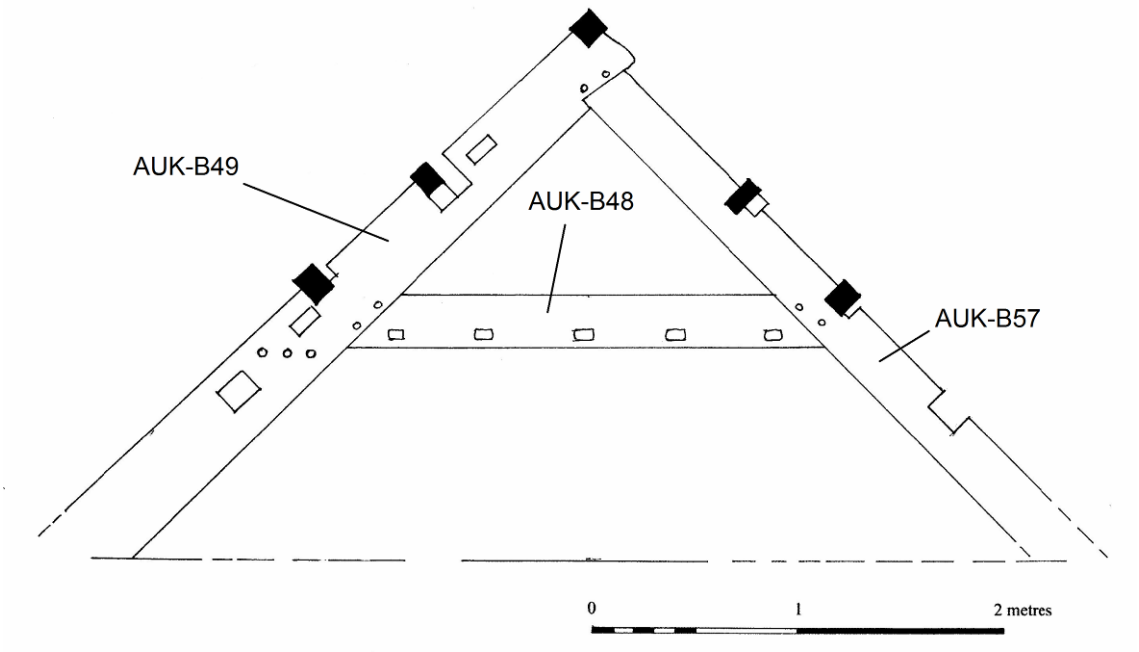

Figure 38: Scotland wing, truss 11 (west face), showing the location of samples AUK-B48, AUK-B49, and AUK-B57 (Peter Ryder)

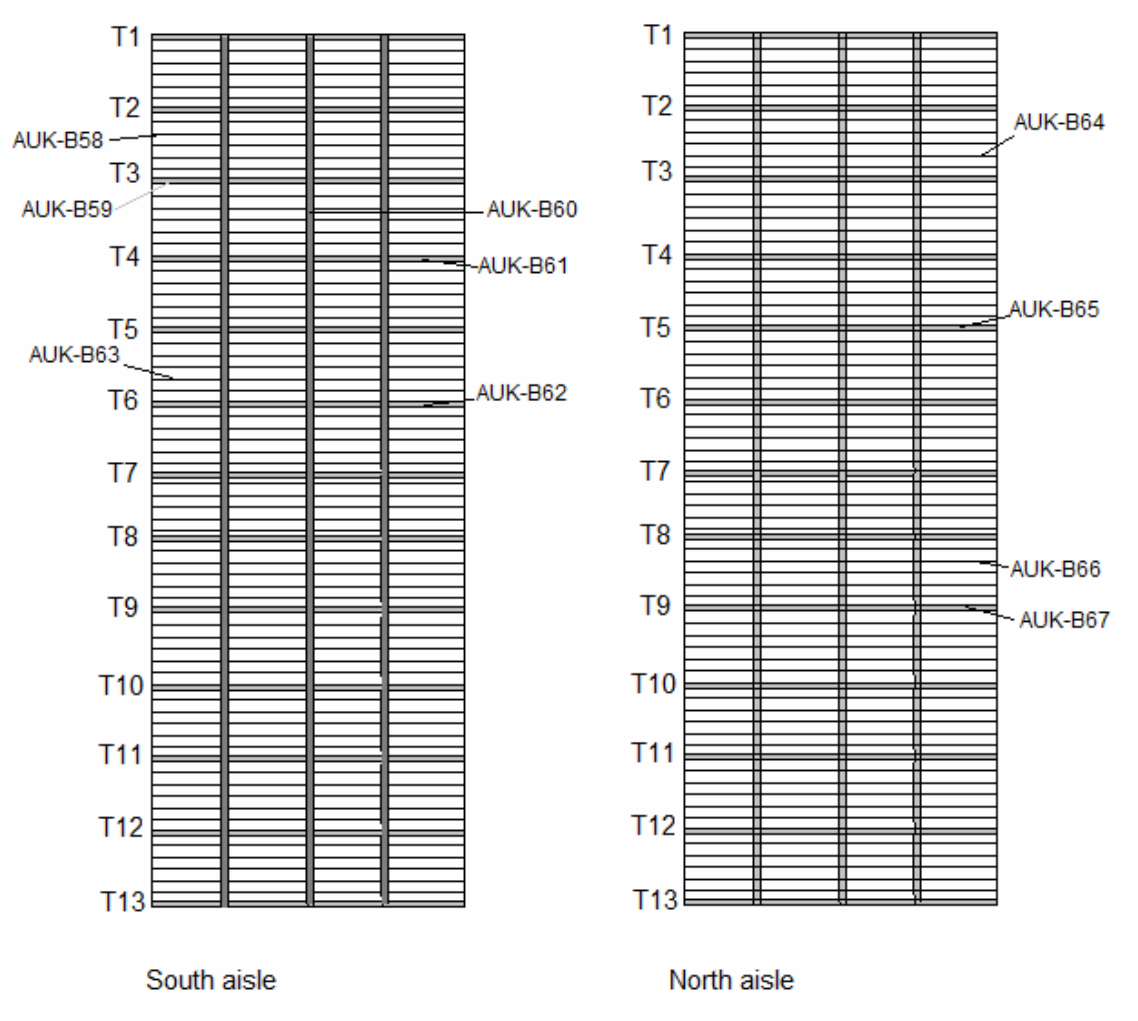

Figure 39: Sketch plans of north and south aisles of the Chapel, showing the location of samples AUK-B58–67

Figure 40: Infill roof, photograph taken by putting camera through entry hatch (Alison Arnold)

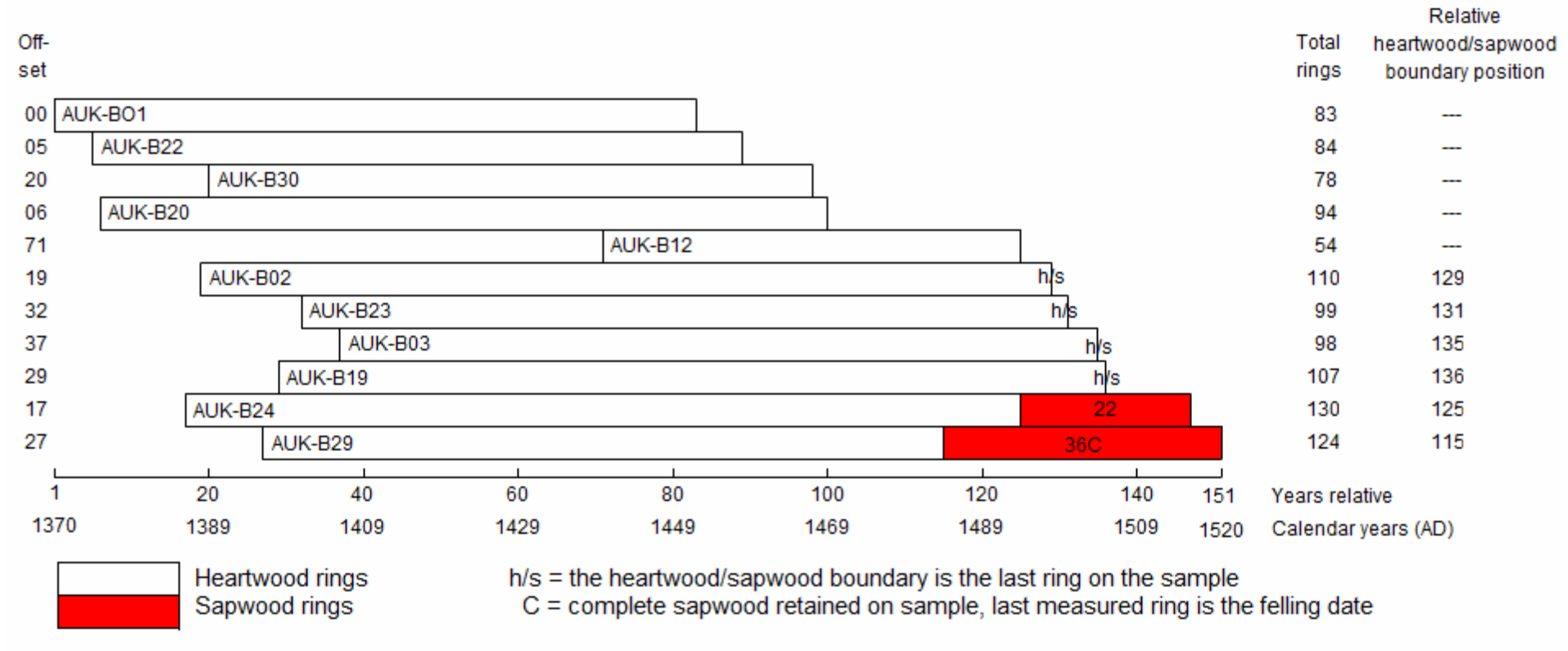

Figure 41: Bar diagram of samples in site sequence AUKBSQ01

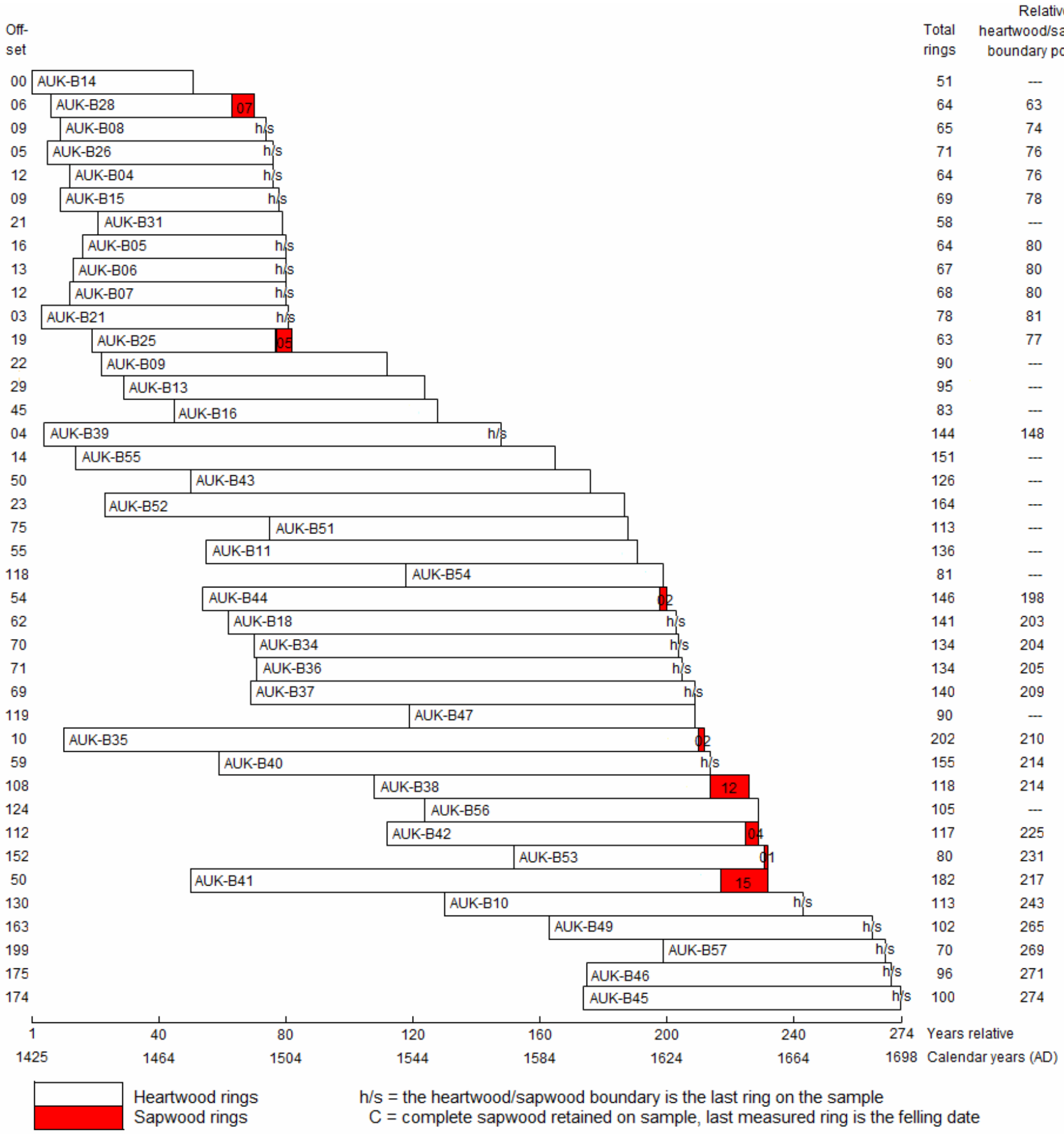

Figure 42: Bar diagram of samples in site sequence AUKBSQ02

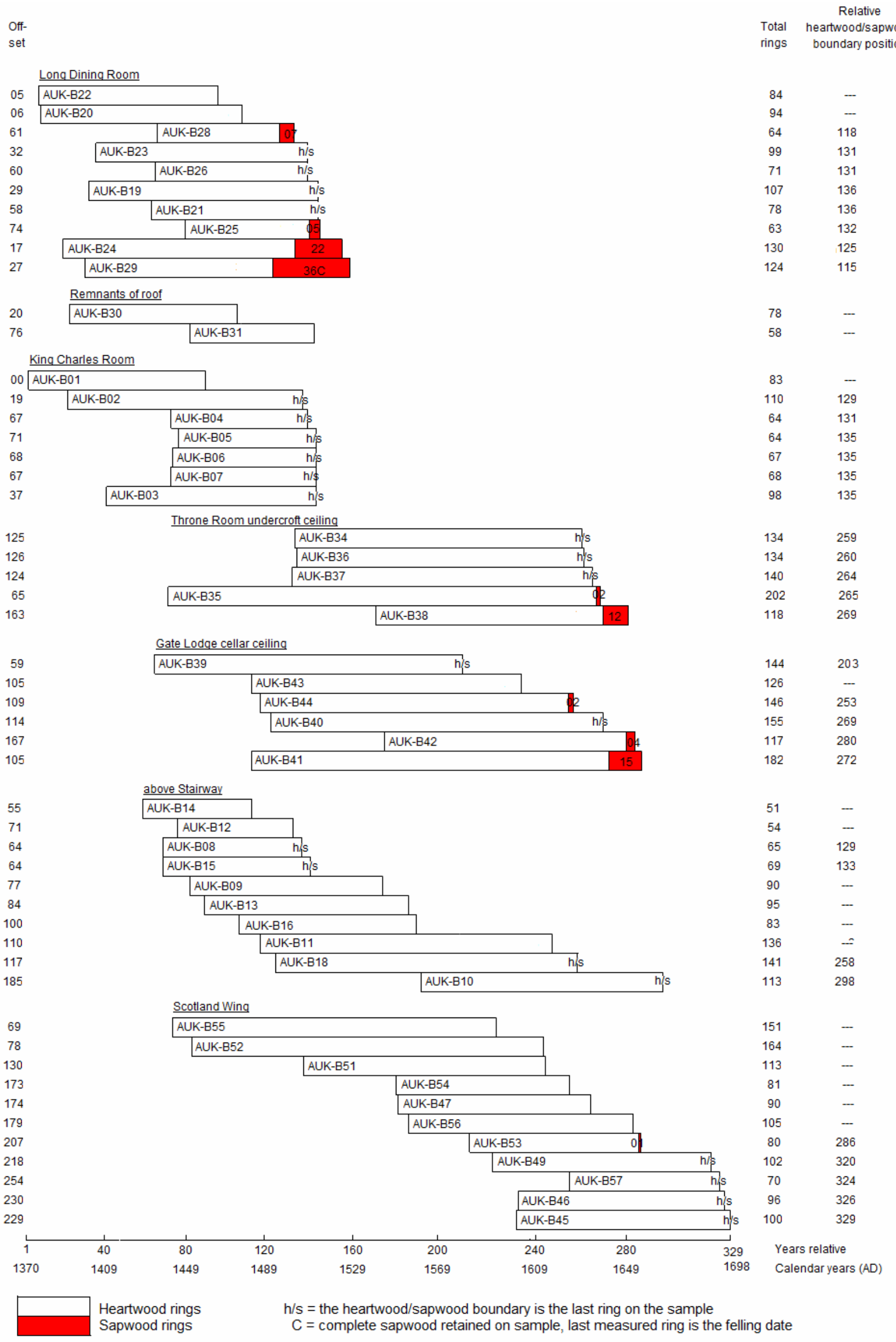

Figure 43: Bar diagram of all dated samples, sorted by area

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

AUK-B01A 83
179 152 200 189 191 187 231 176 245 242 214 239 335 345 241 158 242 266 269 275
268 279 293 374 273 268 375 260 331 273 292 293 232 219 219 222 245 218 327 241
234 228 157 197 184 216 146 150 171 133 256 195 177 152 152 180 124 147 254 227
147 192 237 154 214 215 245 197 200 160 159 174 127 199 163 204 183 226 183 208
191 213 158
AUK-B01B 83
176 150 207 189 187 184 225 180 252 251 216 234 340 348 232 169 253 253 282 269
257 270 293 365 252 284 363 263 335 273 280 315 231 220 216 219 229 208 340 242
237 221 152 195 188 231 142 161 163 123 251 202 174 156 149 172 127 143 242 225
156 180 232 170 206 194 263 195 196 161 159 171 124 204 156 211 182 231 182 196
201 218 185
AUK-B02A 110
363 346 328 324 377 335 272 375 248 307 277 291 229 199 191 166 188 184 185 207
197 173 161 151 161 150 167 107 141 182 116 175 142 150 165 107 136 110 140 204
183 112 164 161 112 142 143 115 134 118 84 74 84 73 101 88 82 84 92 97
101 104 133 112 132 130 104 105 123 135 116 143 78 116 110 96 140 130 143 125
130 96 142 135 184 109 158 185 167 178 97 114 166 136 135 120 105 115 122 109
98 71 93 87 91 78 65 65 70 62
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420 334 340 318 370 349 265 383 254 307 267 300 217 207 197 154 193 182 182 216
209 164 155 157 159 145 161 116 134 172 98 179 156 157 173 107 140 111 128 210
180 122 165 156 100 133 147 118 119 118 82 80 75 76 97 86 84 88 84 107
103 100 127 119 126 133 103 106 124 131 118 143 79 110 117 96 140 131 139 118
132 105 135 128 192 110 157 174 170 178 100 108 176 138 116 127 102 114 129 106
92 75 94 83 90 83 57 72 66 63
AUK-B03A 98
258 327 317 239 206 248 218 242 248 164 177 204 127 251 221 225 186 150 178 130
158 251 221 205 181 248 142 225 259 260 259 245 156 115 159 112 186 151 165 130
165 168 199 193 266 186 186 180 137 167 162 169 149 165 116 123 106 116 146 167
155 98 137 135 129 138 214 149 234 269 190 183 153 147 236 181 198 152 139 139
101 56 64 65 79 65 84 89 75 78 87 73 115 138 92 106 90 83
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300 323 310 250 205 245 229 232 256 168 183 206 131 261 234 231 189 162 191 134
163 251 221 203 168 275 150 211 255 258 273 243 156 115 147 123 192 154 169 130
160 172 193 195 263 190 197 179 140 172 160 169 154 163 102 123 111 115 143 170
142 110 135 132 127 149 207 155 241 277 197 185 152 150 240 180 199 161 131 141
89 71 71 55 80 65 80 91 85 75 75 70 115 138 91 119 80 97
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341 261 201 212 255 309 297 302 293 369 367 478 435 473 463 233 137 136 248 319
249 290 292 233 308 274 234 215 279 270 406 295 328 295 241 232 159 230 190 247
248 269 315 249
AUK-B04B 64
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325 271 197 191 252 315 297 302 289 379 376 484 431 467 456 245 142 146 246 339
226 288 281 231 307 285 229 221 266 267 404 293 324 302 250 232 170 233 205 242
247 272 309 257

AUK-B05A 64
314 302 262 246 255 199 280 256 266 290 299 308 256 331 236 280 229 167 168 210
202 215 158 163 163 245 253 249 199 213 201 147 104 137 190 166 171 189 197 180
192 176 156 148 194 161 177 126 131 143 130 161 78 128 177 171 150 125 184 167
80 105 117 174
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304 304 270 236 256 195 242 262 235 314 296 304 266 329 243 287 223 172 167 204
203 221 157 159 162 262 238 261 193 221 206 142 109 128 183 166 178 186 206 171
199 175 167 142 196 155 174 132 127 135 139 158 88 139 176 179 143 125 177 171
92 101 139 154
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331 471 472 560 353 326 472 365 355 461 426 371 336 360 373 291 372 308 330 325
288 245 228 237 223 232 237 239 353 463 417 328 285 314 278 192 184 237 267 223
194 211 234 241 225 247 210 218 193 230 128 173 216 202 208 151 165 200 204 214
202 272 189 149 118 92 106
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330 476 492 561 356 316 480 371 349 483 418 382 326 354 377 297 388 322 348 332
295 245 225 236 209 243 238 240 364 477 399 330 301 293 278 187 183 255 272 212
192 198 224 225 230 238 220 215 198 224 132 178 203 202 215 152 165 198 217 208
204 267 235 136 118 86 109
AUK-B07A 68
195 237 301 473 621 396 340 513 368 323 438 428 363 346 381 384 310 406 325 334
358 289 248 249 256 214 235 249 269 355 462 363 299 271 279 303 217 187 248 277
233 192 195 204 221 247 242 217 231 207 225 145 176 221 223 232 165 176 215 231
209 198 233 186 125 110 87 131
AUK-B07B 68
217 239 294 473 622 404 340 520 367 326 443 422 369 342 386 389 306 410 325 331
339 291 240 250 248 221 223 241 250 350 454 371 306 269 286 295 206 200 241 238
239 188 202 217 227 230 249 209 224 199 237 139 181 210 207 236 168 168 210 219
221 187 236 186 124 113 98 108
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249 226 280 234 211 184 201 218 180 231 222 214 166 191 203 195 176 230 225 145
180 147 167 180 130 111 105 131 125 86 93 90 126 140 158 116 144 171 118 117
94 134 180 169 165 153 159 150 136 101 104 140 167 210 182 180 219 171 126 73
143 167 194 165 174
AUK-B08B 65
247 223 281 246 206 179 194 227 189 226 224 208 167 178 202 192 180 228 224 158
168 154 177 177 133 130 102 140 113 86 95 95 121 141 144 126 156 164 119 110
110 125 172 161 155 167 155 146 144 94 102 148 158 212 175 180 219 153 128 77
140 164 194 172 159
AUK-B09A 90
168 146 203 179 179 209 181 200 150 186 149 97 99 103 136 135 136 92 112 116
111 179 144 204 279 122 103 122 164 226 192 184 209 194 192 168 149 168 135 147
287 184 185 179 131 78 71 96 108 94 83 103 135 67 66 49 60 71 113 102
98 98 73 87 82 64 104 81 66 93 63 92 58 62 70 94 88 113 74 96
76 78 94 48 92 52 67 72 61 72
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165 156 193 191 174 199 174 202 131 186 163 116 79 120 130 136 129 96 109 103
114 187 142 211 250 126 101 117 164 234 168 176 211 189 195 160 149 165 140 158
251 187 182 179 126 81 67 91 106 98 77 100 141 84 66 48 59 71 111 106
96 111 68 86 85 63 101 87 62 93 65 91 59 53 75 108 92 112 74 94
82 77 88 48 99 53 67 72 58 77
AUK-B10A 113

325 214 215 263 285 314 266 300 374 340 315 237 253 184 304 247 265 229 270 270
217 151 115 161 170 198 123 77 88 105 79 100 95 66 72 67 67 77 91 76
95 92 100 109 76 71 67 46 51 83 60 75 62 77 64 84 84 74 97 84
73 46 56 72 61 73 83 107 103 65 65 47 57 73 121 125 98 123 88 77
77 38 68 126 140 147 179 154 148 142 148 168 134 109 135 145 145 115 123 212
158 151 111 118 95 76 62 57 71 47 50 63 57

AUK-B10B 113

330 217 206 265 279 333 263 302 366 333 321 230 259 192 304 246 257 227 272 269
217 157 114 157 170 204 117 71 89 107 82 103 108 62 75 72 57 76 83 84
96 94 99 110 75 77 63 44 57 80 61 67 69 75 70 80 79 79 95 88
76 37 54 70 66 67 80 105 107 63 66 43 60 75 118 123 101 121 90 73
77 41 66 125 140 151 179 152 149 145 149 163 134 117 123 147 147 122 123 207
169 143 120 109 93 73 67 58 67 45 53 66 58

AUK-B11A 136

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73 52 57 65 73 119 110 120 168 123 158 120 93 149 152 92 119 60 95 54
66 72 82 72 119 96 99 79 92 104 58 89 59 62 57 63 77 99 52 69
57 57 43 52 72 64 70 44 56 32 48 51 47 57 58 63 117 70 55 88
51 57 56 66 87 63 70 36 45 58 67 57 58 73 47 61 34 29 33 47
44 51 41 54 55 36 46 44 36 30 66 87 98 68 58 75 64 54 75 49
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188 191 100 91 143 164 205 372 227 225 255 138 72 57 85 144 187 161 170 161
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63 71 80 73 125 107 93 86 74 117 54 98 44 57 73 63 78 94 55 79
49 50 44 61 64 62 59 47 55 38 38 52 47 63 53 64 111 72 46 97
62 58 69 58 87 67 71 51 44 40 67 54 56 77 56 55 43 39 28 39
48 57 35 53 50 44 41 43 31 36 62 91 100 57 65 66 66 58 62 56
71 45 84 136 175 111 170 190 212 121 180 99 75 69 57 61

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257 194 231 270 189 158 249 320 253 234 313 281 292 295 236 242 257 192 178 179
166 213 188 180 239 196 243 289 255 243 203 172 147 124 181 234 240 250 204 167
172 139 150 162 165 166 201 198 188 138 140 128 174 208

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264 186 236 264 190 165 239 329 247 235 334 267 288 315 225 238 252 190 172 178
176 217 189 182 249 188 248 281 260 243 215 161 152 133 166 255 236 251 202 169
167 134 147 160 167 160 216 194 194 126 129 135 173 179

AUK-B13A 95

184 173 232 228 167 129 124 163 146 154 129 104 146 163 311 242 247 311 142 119
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72 65 85 83 55 98 64 57 62 106 89 80 67 53 62

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179 166 229 237 164 121 129 163 154 151 130 90 154 170 298 249 257 300 148 120
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91 133 164 188 214 209 72 65 69 63 84 152 136 126 148 99 111 92 104 176
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AUK-B14A 51

364 285 295 340 355 283 263 250 260 344 336 296 293 216 178 262 274 292 199 262
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AUK-B14B 51
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65 61 118 218 211 234 304 174 101 133 188
AUK-B15A 69
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126 154 158 149 157 162 154 91 67
AUK-B15B 69
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AUK-B16A 83
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97 126 76
AUK-B16B 83
237 202 234 248 316 283 223 336 160 240 244 193 200 310 162 209 235 236 114 76
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170 142 127 120 127 124 108 108 122 102 93 136 142 123 136 104 140 129 107 108
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99 126 82
AUK-B17A 108
99 86 81 69 73 64 69 84 98 76 101 59 86 94 82 89 109 88 91 103
122 138 114 115 121 100 106 93 86 91 84 60 84 94 85 82 100 106 106 80
91 133 61 72 89 78 107 97 119 102 99 109 114 107 123 174 146 143 165 117
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115 128 133 131 92 96 119 115
AUK-B17B 108
102 81 83 72 62 74 57 89 86 75 96 59 92 88 89 82 101 89 90 105
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94 127 63 75 80 84 100 103 122 96 95 106 110 105 134 166 134 145 169 120
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AUK-B18A 141
204 115 111 105 107 117 97 138 155 206 210 147 190 155 79 81 67 102 99 79
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67 93 79 97 145 102 104 79 111 121 85 92 100 79 97 80 92 78 70 70
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47
AUK-B18B 141
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77 78 84 70 68 58 88 79 59 61 69 69 70 97 77 62 78 75 99 75

63 98 80 89 154 98 101 79 109 128 85 97 96 90 94 83 88 85 67 70
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44

AUK-B19A 107

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168 128 120 129 119 169 182

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103 141 132 59 87 111 158 159 188 199 163 141 134 128 143 131 134 151 132 142
160 134 116 132 132 161 174

AUK-B20A 94

67 95 156 147 96 96 105 84 92 79 120 140 163 160 231 242 270 372 342 188
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65 86 161 149 101 85 112 82 92 77 131 139 163 160 220 232 266 375 331 184
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260 285 224 222 225 175 251 257 261 244 323 390 349 304

AUK-B21A 78

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169 296 201 202 316 85 144 141 169 206 236 242 129 68 62 104 112 126

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577 687 516 441 430 377 511 524 480 345 305 252 389 452 343 404 342 268 241 290
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167 284 209 202 307 88 133 139 166 209 235 242 133 70 53 112 125 123

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258 365 186 253 300 295 181 181 142 136 190 185 65 125 120 128 138 192 133 105
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122 132 112 90 119 128 133 127 154 110 128 102 87 99 107 85 122 89 102 92
105 86 79 70 110 131 123 119 153 117 146 108 117 102 106 97

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124 83 105 108 88 122 93 109 109 146

AUK-B23A 99

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72 104 176 218 244 304 334 273 221 243 212 248 229 286 257 218 233 274 203
AUK-B23B 99
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210 324 317 278 139 112 203 208 245 370 293 318 340 253 310 310 247 196 237 205
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AUK-B24A 130
392 283 196 195 189 381 251 347 175 278 231 271 282 264 183 136 129 176 134 160
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119 170 142 144 157 118 82 80 163 157 107 131 95 79 81 40 73 108 84 115
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AUK-B24B 130
400 280 199 198 182 378 254 342 178 279 237 262 284 259 183 142 137 168 134 154
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117 168 143 146 160 118 75 93 160 153 115 134 92 72 74 33 84 107 86 121
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65 135 95 102 99 77 71 89 86 110
AUK-B25A 63
363 286 348 364 300 365 252 246 289 335 293 209 316 295 330 264 293 312 328 264
230 263 341 393 375 335 336 298 157 109 94 140 177 220 165 187 135 219 186 157
151 154 158 229 168 178 197 167 219 181 202 211 267 204 192 220 195 94 99 79
131 141 146
AUK-B25B 63
355 303 337 363 290 369 263 245 292 328 290 192 317 286 329 253 296 314 317 260
240 257 338 399 381 321 332 297 153 115 71 148 190 218 144 186 141 217 180 156
162 159 159 231 171 179 187 178 210 170 197 214 251 206 204 211 211 99 82 91
132 140 165
AUK-B26A 71
556 450 517 428 586 529 527 521 451 362 435 517 480 473 401 338 286 323 234 275
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230 297 116 109 145 247 243 153 144 114 163 222 170 146 122 220 188 266 152 161
151 133 174 102 115 144 131 131 118 131 112
AUK-B26B 71
597 461 503 428 570 538 536 509 465 350 443 521 468 458 404 335 298 333 231 261
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152 131 172 106 109 150 137 127 122 135 108
AUK-B27A 67
347 278 311 307 272 410 382 404 378 432 315 377 373 374 288 261 217 267 154 203
225 163 221 204 226 266 215 188 153 199 206 265 191 288 184 262 290 208 164 90
134 158 185 153 209 193 138 149 142 146 191 209 113 59 112 127 134 145 60 89
72 113 114 151 130 126 107
AUK-B27B 67
335 273 309 315 249 356 417 391 373 420 314 378 374 385 290 250 231 259 154 205
223 164 216 205 220 253 212 197 153 199 199 266 192 288 185 256 283 219 161 82

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77 116 112 142 135 128 115
AUK-B28A 64
509 366 318 453 450 382 343 332 336 449 484 425 351 352 240 206 268 196 220 220
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199 170 230 143
AUK-B28B 64
502 366 314 462 451 397 342 326 332 451 482 424 365 345 221 194 260 204 220 221
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244 112 90 114 234 320 249 296 359 301 346 323 249 175 182 237 325 229 284 257
186 167 218 158
AUK-B29A 124
175 202 146 153 133 147 158 167 143 123 124 117 81 92 70 131 137 120 95 118
106 161 100 111 122 153 168 140 88 96 78 115 149 108 112 122 76 94 74 102
106 79 86 79 80 74 74 79 56 51 67 82 93 88 81 109 97 80 82 89
106 72 81 79 50 84 75 77 73 92 73 84 84 65 76 61 80 37 60 71
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AUK-B29B 124
173 207 136 164 131 128 155 161 152 121 134 105 99 91 74 120 136 121 104 110
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AUK-B30A 78
200 179 315 240 291 157 250 235 247 639 640 368 364 304 333 233 254 222 248 350
218 237 264 172 196 131 185 175 262 189 302 133 190 174 204 121 91 132 176 213
93 196 181 148 147 158 204 179 144 121 168 149 177 164 203 125 107 133 145 185
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AUK-B30B 78
249 167 305 266 286 148 266 220 257 619 666 359 369 295 333 230 240 230 249 358
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181 150 263 181 203 170 166 151 143 124 139 146 133 141 166 201 177 176
AUK-B31A 58
279 312 376 340 319 359 352 303 276 238 326 265 239 243 264 248 288 184 245 230
331 283 307 224 262 254 269 240 194 265 307 262 236 285 215 243 308 248 181 218
213 252 199 198 213 211 241 210 220 211 246 205 234 259 290 151 154 135
AUK-B31B 58
283 308 381 342 315 362 346 301 282 240 318 263 242 236 272 238 296 183 237 236
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AUK-B34A 134
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AUK-B35A 202
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136 159 244 215 235 229 179 199 156 110 76 77 104 117 185 180 168 179 158 111
77 53
AUK-B36A 134
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59 52 55 94 186 91 181 134 132 124 197 144 74 82 112 49 56 97 143 113
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AUK-B36B 134
265 224 176 304 427 212 140 102 89 103 134 163 211 232 278 186 165 96 103 93
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91 143 118 171 158 111 135 95 112 110 78 70 81 66 64 139 127 150 114 316
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AUK-B37A 140
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274 297 264 209 208 174 169 165 104 121 116 166 161 143 168 139 106 100 163 132
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114 130 165 97 117 115 113 109 91 62 147 260 271 310 322 341 389 326 259 261
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120 103 168 280 219 268 163 191 228 126 62 89 115 186 156 178 148 149

AUK-B38B 118

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192 164 225 177 182 187 177 238 194 162 125 133 159 156 190 162 168 162 211 161
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143 186 178 143

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159 178 205 175 184 187 184 230 184 163 130 128 152 157 180 163 164 170 208 160
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132 206 169 140

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AUK-B41A 182
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AUK-B42A 117
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123 146 184 83 65 77 98 169 156 159 147 101 175 98 114 123 149 187 179 176
208 176 140 157 135 157 168 117 127 191 131 173 135 189 148 130 116 92 139 163
175 137 157 228 178 237 260 222 304 273 326 189 266 213 241 200 239 150 176 148
AUK-B45B 100
197 134 127 115 177 181 208 188 236 282 223 175 155 198 179 173 222 152 187 212
161 192 167 232 162 146 96 141 118 131 185 118 167 141 94 107 84 97 116 148
129 148 178 89 64 81 91 160 152 145 168 100 173 106 101 129 146 185 174 176
210 166 136 158 139 156 161 125 129 190 131 176 124 187 143 128 117 98 146 162
158 132 171 209 178 230 254 221 301 262 335 185 247 218 233 181 241 166 192 151
AUK-B46A 95
103 101 133 130 140 156 172 181 117 140 114 87 115 102 163 126 129 178 149 205
172 233 134 125 93 113 114 118 146 92 114 126 103 89 72 81 97 130 84 136
154 66 55 81 66 127 95 98 94 58 120 96 69 89 97 125 98 116 178 111
92 90 91 119 121 78 116 158 155 132 125 143 115 101 83 99 133 153 144 144
165 232 142 171 186 226 289 297 297 183 223 175 177 204 218
AUK-B46B 96
118 108 96 138 126 133 157 174 188 117 138 102 99 115 103 169 123 140 193 146
209 170 229 147 120 82 114 128 107 152 91 122 117 101 82 70 87 97 124 99
125 161 61 59 75 66 128 92 104 101 67 120 87 60 91 98 130 95 117 171
120 90 91 98 124 126 77 106 158 142 136 123 140 130 95 92 95 131 153 144
139 163 236 135 179 189 217 287 295 296 180 233 170 176 207 212
AUK-B47A 90
208 192 155 143 205 159 199 249 196 191 180 232 258 127 111 185 183 203 184 189
189 115 169 153 89 105 120 113 118 161 136 116 106 99 70 97 113 76 76 78

76 52 74 69 48 49 48 41 43 85 94 82 39 25 30 27 43 28 33 25
46 39 34 29 47 45 42 43 40 36 56 70 77 56 72 65 75 71 62 47
40 34 31 26 20 28 25 28 27 28

AUK-B47B 90

215 193 141 130 200 154 205 246 189 179 180 231 237 138 102 180 180 205 172 190
189 111 172 142 88 100 120 119 96 176 136 121 103 96 72 101 106 81 71 93
75 61 84 74 57 57 41 39 59 70 95 76 35 26 33 30 39 23 34 28
51 30 31 36 50 47 40 43 34 42 57 72 71 57 70 66 74 75 60 42
39 28 27 31 20 27 30 30 24 25

AUK-B48A 86

170 143 152 207 269 307 216 242 249 280 188 198 166 224 145 194 211 209 185 162
173 174 150 133 146 145 131 156 181 228 231 181 126 158 146 113 115 105 87 91
130 82 118 116 155 151 162 142 107 130 117 129 124 155 161 107 110 120 91 133
144 137 129 132 121 148 113 88 84 107 142 125 118 122 125 113 109 108 94 86
106 222 127 98 72 72

AUK-B48B 86

157 143 144 217 274 301 214 241 253 278 195 201 169 209 163 198 214 196 193 164
175 169 156 133 147 147 136 152 177 243 235 180 125 150 152 118 116 100 93 89
102 110 118 134 167 152 160 140 110 138 108 130 124 159 158 115 112 123 86 135
143 134 128 130 125 148 109 88 89 106 143 127 114 129 120 111 113 105 96 84
107 213 138 89 80 66

AUK-B49A 102

240 296 188 176 249 279 252 279 217 199 155 147 137 97 67 114 121 95 121 128
72 60 81 59 86 78 101 121 100 121 65 39 59 54 64 65 49 40 48 60
67 103 119 106 125 73 65 71 106 120 163 112 124 104 58 60 52 99 93 90
117 137 124 141 94 94 91 86 101 81 96 88 93 76 70 92 91 106 74 92
126 121 145 142 135 143 147 148 140 157 183 192 132 104 154 122 158 119 146 204
197 167

AUK-B49B 102

245 315 202 176 254 285 259 270 220 206 150 144 149 100 69 102 121 80 128 134
68 64 86 60 85 84 107 112 99 119 56 46 56 57 63 62 52 41 42 77
59 102 111 116 125 65 72 69 107 127 160 111 120 114 70 47 59 102 92 92
110 140 122 137 97 91 92 85 101 80 101 85 92 75 69 95 95 104 73 89
122 128 148 152 134 152 146 155 135 155 181 192 130 102 154 119 154 123 150 203
194 170

AUK-B51A 113

157 97 53 82 83 110 162 112 188 150 120 154 159 185 167 128 158 105 140 107
122 236 274 167 206 215 225 159 116 205 180 194 107 182 205 229 219 214 182 211
267 187 189 144 152 167 132 84 125 81 97 185 158 157 154 216 187 159 149 190
170 163 192 202 205 170 159 76 75 105 157 131 109 124 119 78 57 55 90 121
187 147 178 147 181 120 164 95 126 144 143 105 115 133 162 192 121 135 151 110
121 116 124 171 192 161 175 124 122 129 141 140 146

AUK-B51B 113

156 93 62 80 77 108 160 124 192 155 119 149 158 189 161 130 161 106 156 94
126 237 264 168 204 218 209 173 127 200 181 181 115 167 203 231 219 215 179 192
246 193 193 137 163 180 143 83 132 89 100 183 151 161 157 211 185 165 149 189
166 169 186 202 202 182 153 83 75 113 158 122 110 118 123 85 49 63 87 124
183 148 157 164 180 119 162 101 120 141 144 109 116 130 162 193 130 124 150 115
116 114 117 182 195 157 160 126 111 132 133 136 167

AUK-B52A 164

167 170 104 137 177 180 155 140 138 124 145 122 125 147 182 189 163 160 196 257
224 198 175 189 150 128 105 154 173 194 201 220 225 227 220 236 204 190 202 273
169 155 161 142 183 137 153 141 204 153 131 133 148 96 81 91 139 162 175 165

172 126 107 85 108 110 100 105 123 114 85 126 135 75 83 77 92 106 136 127
102 115 119 120 99 95 128 131 117 106 121 122 147 117 88 84 91 102 75 90
80 68 55 88 75 80 98 140 126 112 124 155 151 168 117 111 136 117 97 57
43 58 59 53 44 53 58 51 43 33 39 56 56 64 100 87 78 90 74 48
64 52 43 43 57 56 57 48 47 40 25 32 33 34 51 70 94 93 84 91
78 97 72 115

AUK-B52B 164

137 176 119 131 198 184 162 112 163 135 143 124 131 163 206 204 168 165 198 275
230 208 193 185 179 126 110 153 184 207 206 229 234 224 238 236 223 204 188 254
185 173 159 149 184 144 142 154 203 157 132 136 148 96 76 88 133 168 172 164
184 130 119 86 105 108 109 103 125 96 101 133 136 86 88 78 97 115 129 135
110 110 125 130 93 106 128 131 119 107 121 130 151 120 85 80 93 106 73 104
81 60 60 84 82 74 102 139 122 115 133 141 154 171 124 111 139 112 105 57
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68 50 46 46 51 60 60 44 42 42 27 30 27 30 53 71 94 97 78 92
77 101 77 109

AUK-B53A 80

74 126 144 162 115 107 140 150 179 201 163 156 162 131 107 135 165 151 153 120
142 172 134 107 112 127 163 121 110 129 120 127 104 111 100 115 147 135 144 166
183 188 153 175 168 203 188 129 100 134 184 171 187 136 155 149 107 77 64 43
56 79 66 92 106 88 78 66 82 99 89 90 104 85 100 56 92 95 118 125

AUK-B53B 80

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152 167 135 113 117 117 167 133 102 119 113 129 110 103 99 115 135 136 150 162
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52 73 58 96 97 90 80 62 70 114 82 96 93 80 102 62 86 98 110 126

AUK-B54A 81

96 80 91 78 84 82 91 82 136 136 126 130 172 129 87 62 128 110 130 160
182 187 109 146 102 85 101 100 108 110 198 171 162 150 156 98 151 159 109 114
117 117 80 129 114 85 76 70 49 65 75 95 94 55 45 51 38 57 56 43
41 51 45 62 51 55 48 50 61 48 70 83 90 93 80 82 72 74 61 49
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AUK-B54B 81

102 97 78 81 76 81 85 94 125 130 137 139 166 123 92 53 131 101 128 158
176 181 113 146 96 90 96 95 104 124 183 169 160 143 155 98 148 155 105 111
121 108 82 126 123 82 72 65 52 62 75 77 93 53 41 54 39 56 52 47
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AUK-B55A 151

228 219 205 161 233 223 196 147 143 146 154 102 98 141 114 92 58 95 71 55
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139 134 147 122 105 125 103 112 136 104 94 89 90 118 88 93 92 119 102 115
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83 148 91 65 77 70 50 48 38 49 49 51 91 52 53 66 90 78 69 68
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AUK-B55B 151

200 214 205 183 211 218 184 152 145 144 152 105 102 146 112 94 61 95 71 56
68 75 106 96 97 107 112 134 172 140 85 100 98 86 83 76 92 119 143 115
132 130 148 124 103 128 102 111 138 99 99 89 91 116 90 97 93 116 102 119
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76 163 89 61 77 67 52 48 50 39 62 49 105 51 54 59 97 80 69 67
83 70 75 53 55 60 46 52 46 42 52 60 56 53 87 94 62 40 36 39
58 85 64 56 65 53 44 53 43 45 49

AUK-B56A 105

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123 151 138 121 128 133 167 98 56 87 111 168 153 116 117 176 184 218 120 99
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111 103 93 77 116 126 113 161 146 181 176 146 157 154 189 128 109 97 129 126
153 141 140 132 125 85 59 32 39 55 46 66 76 52 62 57 70 85 78 80
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AUK-B56B 105

235 150 247 192 167 190 254 142 198 131 174 177 194 166 174 162 138 145 129 99
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72 79 76 62 78

AUK-B57A 70

128 72 74 85 132 197 182 138 132 94 87 93 134 129 167 122 132 153 86 77
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194 160 277 239 249 245 122 275 234 168

AUK-B57B 70

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AUK-B58A 65

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237 240 269 165 165

AUK-B58B 65

695 554 427 619 549 610 467 456 699 478 635 393 432 472 375 427 427 397 251 246
305 302 227 229 167 255 409 293 263 445 262 329 232 322 184 186 100 285 171 189
125 167 182 178 185 190 137 281 140 286 154 196 192 176 207 341 326 229 232 261
246 232 281 162 167

AUK-B59A 57

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170 103 139 167 219 231 230 210 245 334 92 117 92 106 155 132 208 169 155 199
211 131 46 77 57 105 163 170 170 215 159 216 247 237 247 253 263

AUK-B59B 57

232 186 175 181 141 157 132 178 138 162 187 180 260 349 399 487 485 401 404 373
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202 126 41 65 65 107 145 165 189 226 168 219 246 239 237 279 251

AUK-B60A 58

431 339 388 539 619 577 228 269 288 289 253 281 247 246 251 232 237 270 339 291
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AUK-B60A 58

409 328 389 541 714 616 229 264 288 284 257 270 236 241 244 214 242 292 318 285
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AUK-B61A 58
197 202 241 367 227 300 254 225 234 308 388 835 785 278 328 289 301 287 371 427
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244 244 296 330 306 354 370 381 349 435 407 343 220 296 437 276 356 325
AUK-B61B 58
194 200 235 332 252 288 262 224 221 298 398 855 798 285 334 286 298 292 374 433
303 293 324 378 272 359 257 311 196 350 232 209 273 317 304 266 318 286 252 277
239 242 270 331 310 365 396 369 366 456 406 339 246 281 399 286 188 185
AUK-B62A 57
414 160 258 248 364 307 297 373 420 477 544 490 443 403 695 546 288 240 206 210
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158 168 168 199 176 268 242 330 266 236 267 186 265 265 143 120 130
AUK-B62B 57
429 163 251 244 370 386 292 400 440 465 484 474 435 388 730 560 308 241 206 232
288 359 336 298 415 403 400 409 439 412 192 249 218 397 526 416 461 318 356 399
157 174 161 194 183 271 255 325 269 230 263 197 275 263 133 118 132
AUK-B63A 65
372 322 391 405 400 410 425 406 314 335 297 392 258 322 285 246 253 74 41 41
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AUK-B63B 65
400 323 401 403 398 411 428 411 299 345 302 385 254 335 273 258 246 84 35 40
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76 65 83 69 99 95 104 100 84 94 111 134 56 28 36 48 55 86 83 96
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AUK-B64A 68
172 235 184 234 151 184 367 219 250 219 143 188 153 274 212 314 134 185 234 225
177 165 188 187 218 174 184 130 153 143 166 148 208 200 205 152 147 124 77 49
64 54 55 87 75 111 88 119 98 106 132 102 103 110 137 154 148 200 186 117
158 85 88 83 123 149 139 151
AUK-B64B 68
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182 168 190 189 210 181 178 135 147 145 166 155 210 201 209 158 152 131 61 41
54 40 54 81 66 110 91 114 99 109 126 100 108 110 131 153 142 201 198 119
149 82 84 83 122 152 120 162
AUK-B65A 61
233 296 182 176 238 253 316 330 255 163 236 319 364 324 268 329 324 244 191 265
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99 226 233 164 115 69 88 121 92 204 95 98 153 158 148 95 69 74 66 82
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AUK-B65B 61
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AUK-B66A 57
155 141 106 107 129 152 173 141 168 159 87 83 115 130 164 111 102 186 133 149
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92 80 61 107 83 94 114 58 88 94 77 65 79 91 100 88 90
AUK-B66B 57
152 139 102 111 130 150 165 138 165 151 96 75 117 130 164 109 112 173 132 172
136 118 129 116 123 118 125 122 119 77 53 70 88 90 79 100 102 76 51 76

93 84 62 106 92 97 112 70 79 89 79 59 75 91 120 95 100
AUK-B67A 59
198 152 72 110 115 101 169 97 140 179 132 113 94 126 210 214 126 149 181 140
174 144 153 141 179 239 178 143 108 98 99 64 54 61 49 63 54 90 71 70
105 160 131 81 109 131 148 129 171 119 109 89 87 159 134 91 55 66 60
AUK-B67B 59
170 158 65 125 122 103 163 94 143 178 134 107 99 131 198 216 137 154 178 139
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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 Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring..

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It

also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

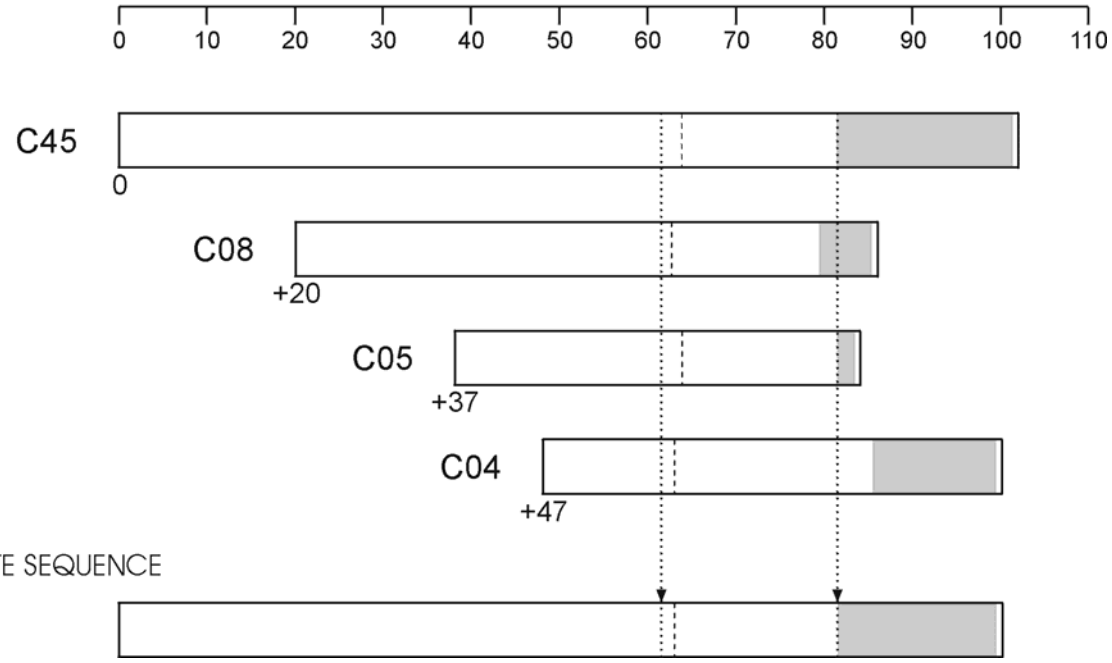


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

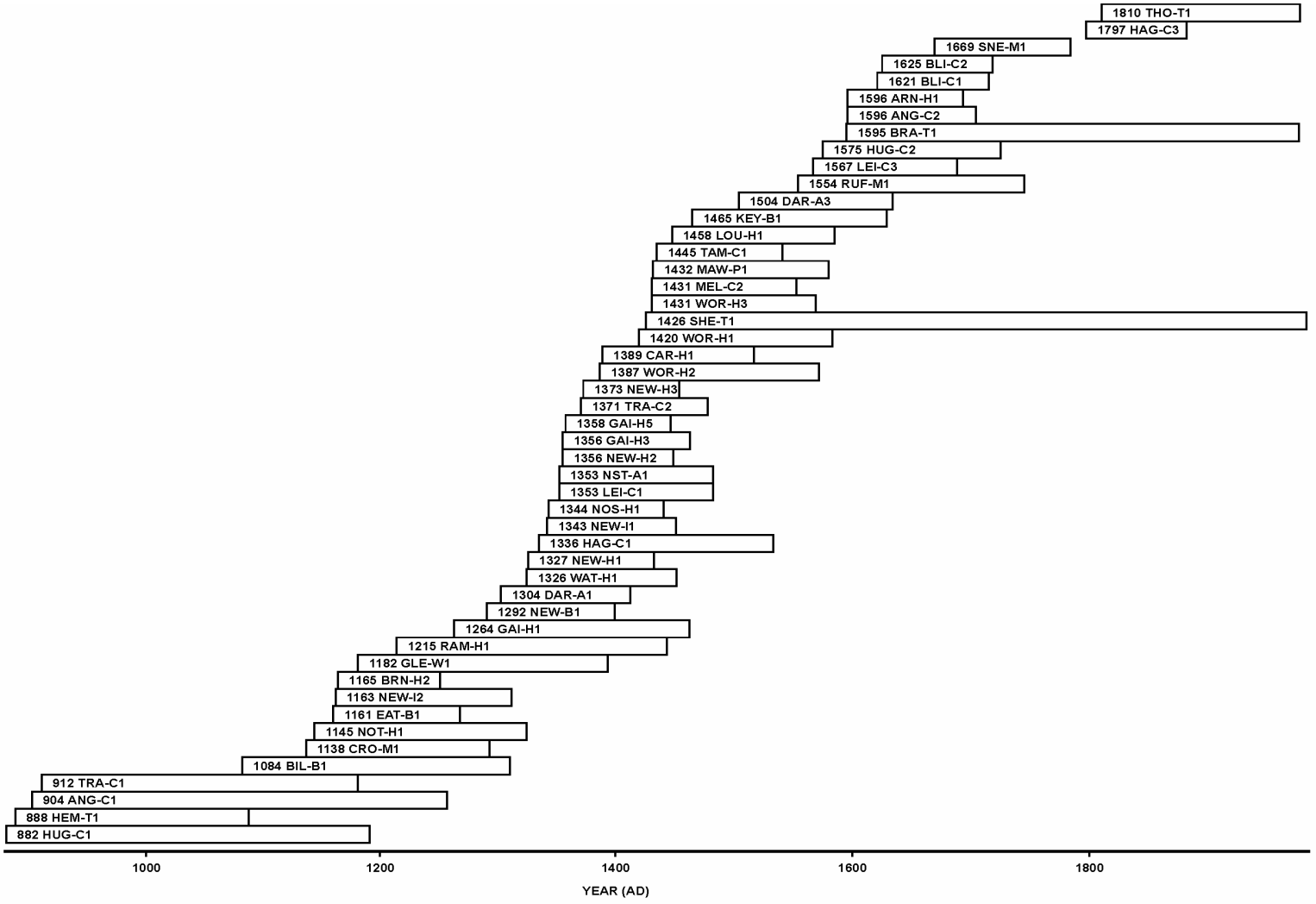
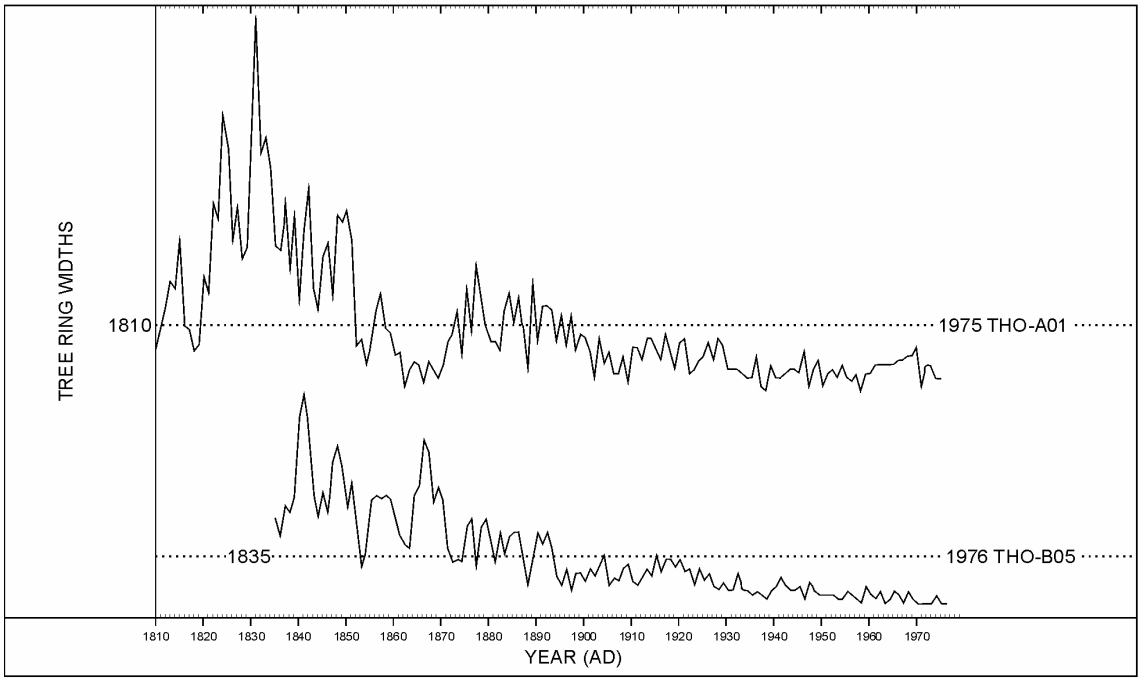


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

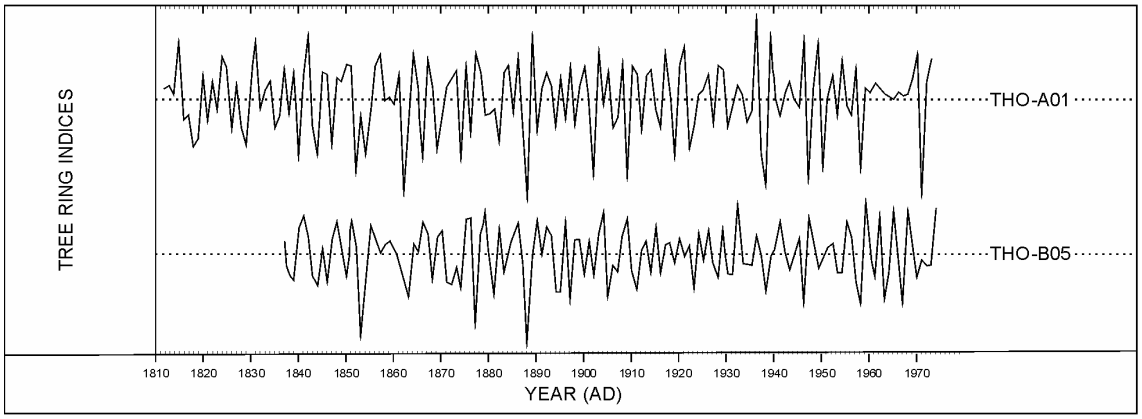


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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