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Bunksland Farmhouse
East Anstey
Devon

Tree-ring Dating of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

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Front Cover: Bunksland Farmhouse in Devon © Historic England. Photograph Alison Arnold

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SUMMARY
Tree-ring analysis was undertaken on samples taken from timbers of the roof and ground floor of this farmhouse, resulting in the successful dating of 14 of them. The timbers of the roof are now known to have been felled in AD 1396–7, demonstrating that the house was constructed at the end of the fourteenth century. A ground floor doorframe was constructed of timbers felled in AD 1507–32 and is likely to be coeval with a fireplace bressummer beam felled in AD 1515–32. These represent a secondary phase of building work.

CONTRIBUTORS
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ACKNOWLEDGEMENTS
We would like to thank Rhiannon Rhys (Historic England Inspector of Historic Buildings & Areas) for help with the start-up of this work and Rebecca Lane (HE Senior Architectural Investigator) for facilitating access and providing the drawings used in this report to locate the samples. Shahina Farid (HE Scientific Dating Team) commissioned and facilitated this study.

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DATE OF INVESTIGATION
2019

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INTRODUCTION

Bunksland Farmhouse, constructed of rough stone and cob, is a multi-phased farm dwelling with attached linhay to the east and shippon and dairy to the west, located in the parish of East Anstey (Fig 1). The earliest phase of building fabric identified in the present building is the surviving elements of a four-bay hall house, thought to date to the late-fourteenth or early fifteenth century. This was remodelled in the sixteenth and seventeenth centuries and again altered in the nineteenth century (Lane forthcoming; Fig 2). It is listed at Grade II* (LEN 1106670) and is on the Heritage at Risk Register due to its current state of decay and collapse.

Roof

There are three roof trusses over the farmhouse thought to belong to the primary, late fourteenth-/early fifteenth-century construction. One of these (Truss 3) would have originally divided the hall from the high (or western) end. This truss comprises principal rafters, a collar supported by curved braces, and, unusually for Devon, a central post reaching to the ridge, giving the appearance of a king-post truss (Fig 3). It is possible that a horizontal beam (now missing) was positioned at the current first-floor level with further braces curving down to it. Trusses 1 and 2 are of a different form being of jointed cruck type with high cranked collars and, in the case of Truss 1 at least, a yoke supporting the diamond-set ridge piece. Between the trusses are a single set of original purlins and some surviving windbraces (Fig 4).

Ground-floor timbers

Potentially also primary, or possibly a very early modification, is the ceiling of the high-end bay forming a separate, upper chamber. This consists of a central, chamfered spine beam with two, also chamfered, half beams to the north and south and squared joists between (Fig 5).

Another early alteration, possibly dating from the early sixteenth century, is the large, stone cross-wall and chimney, which divides the cross-passage from the hall and partially incorporated Truss 2 (Fig 6). A fine, carved doorway between the cross-passage and hall (Fig 7) may be contemporary with this insertion as might be the ceiling in the low end.

The first-floor frame of the hall and cross-passage are thought to be a little later, possibly dating to the early seventeenth century. The floor of the hall is supported on three chamfered and stopped cross beams whilst that of the cross-passage has a series of transverse, squared beams running from the stone partition to the low-end partition.

Further additions and modifications occurred in the seventeenth and eighteenth centuries, notably the construction of the linhay which is thought to have been originally a detached building that was incorporated within the farmhouse sometime later.

The nineteenth century saw the addition of a stable block with hayloft above attached to the western end of the farmhouse. Within the farmhouse, this period saw the insertion or reconstruction of the chimney serving the western bay (Fig 8), allowing the installation of a range; this part of the building no longer being the high-end parlour but serving as the kitchen.

SAMPLING

Dendrochronological analysis was requested by Rhiannon Rhys, Historic England Inspector of Historic Buildings and Areas, to provide independent dating evidence for the primary construction and subsequent development of the farmhouse and its outbuildings and to understand its significance in order to inform structural repairs and long-term stabilisation.

The building is currently very unstable, and so sampling was not possible at this time in the linhay, shippon, or in parts of the western and eastern bays of the farmhouse itself. However, thirty oak (*Quercus* spp) timbers were cored from the roof and ground floor of the farmhouse, with each sample being given the code BNK-D and numbered 01–30. One of the common joists of the first-floor frame (BNK-D13) was sampled twice in an effort to get as long a ring width sequence as possible. The two ring-series crossed matched ($t = 5.4$) and were combined to form the 86-year timber series used for subsequent analysis. Further details relating to all samples can be found in Table 1. The location of sampled timbers has been indicated on Figures 6, 9, and 10. Trusses have been numbered from east to west, and ceiling joists from north to south.

ANALYSIS AND RESULTS

Three of the samples, one from a ground-floor ceiling beam and two from the roof, were deemed to have too few rings (≤40) for secure dating and were therefore rejected prior to measurement. The remaining 27 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. The data of these samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in 20 samples matching to form five groups.

Firstly, ten samples matched each other at a minimum value of $t = 3.7$ and were combined at the relative offset positions to form BNKDSQ01, a site sequence of 76 rings (Fig 11). This site sequence cross-dated consistently and securely against a series of reference chronologies for oak at a first-measured ring date of AD 1322 and a last-measured ring date of AD 1397 (Table 2).

Four other samples also matched each other (at a minimum t-value of 4.2) and were again combined at the relevant offset position to form a second site sequence of 134 rings, BNKDSQ02 (Fig 12). This site sequence was found to span the period AD 1381–1514 (Table 3).

Three further site sequences of 97 rings (at a *t*-value of 5.1), 90 rings (at a *t*-value of 10.1), and 52 rings (at *t*-value of 5.0), each containing two samples, were constructed (Figs 13–15) but attempts to date these and the remaining ungrouped samples were unsuccessful and all remain undated.

INTERPRETATION

Analysis has resulted in the successful dating of 14 samples (Fig 16), ten from the roof and four from ground-floor timbers. Felling date ranges, where quoted, have been calculated using the generic estimate that 95% of mature oak trees have between 15 and 40 sapwood rings. However, it should be noted that three of the five samples with complete sapwood from the roof have fewer than 15 sapwood rings. This has previously been noted in the county (eg Groves 2005) and is addressed in Tyers *et al* (forthcoming).

Roof

Five of the samples taken from the roof have complete sapwood. In the case of four of these the last-measured ring date is AD 1397, the felling date of the timbers represented. The last-measured ring date of the fifth sample with complete sapwood is AD 1396, demonstrating that this timber was felled a year earlier. The remaining five samples all have the heartwood/sapwood boundary ring, the dates of which are broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1380, allowing an estimated felling date to be calculated for the five timbers represented to within the range AD 1395–1420, consistent with these timbers also having been felled in, or around, AD 1396–7, particularly bearing in mind the relatively low numbers of sapwood rings present on those roof timbers with complete sapwood.

Ground-floor timbers

Three of the dated samples from the ground floor were taken from timbers associated with the doorframe between the cross-passage and the hall. Only one of these has the heartwood/sapwood boundary, the date of which allows an estimated felling date to be calculated for the timber represented to within the range AD 1507–32. The other two samples have *terminus post quem* dates for felling of AD 1450 and AD 1491, which makes it likely that they were also felled in AD 1507–32.

A sample taken from the fireplace bressummer in the hall has a date of AD 1479 for the heartwood/sapwood boundary ring. Allowing for the 35 rings of sapwood surviving, an estimated felling date within the range AD 1515–19 can be provided.

DISCUSSION

Prior to tree-ring dating being undertaken the oldest surviving timberwork in Bunksland Farmhouse was thought to date to the late-fourteenth or early fifteenth century. The roof has now been shown to utilise timber felled in AD 1396–7, suggesting construction occurred at the very end of the fourteenth century, in the earlier part of the date-range ascribed on typological grounds. The other potentially primary timbers were those associated with the ground-floor ceiling in the high (or west) end but unfortunately, neither of the two samples taken from this has been dated.

The doorway from the cross-passage to the hall and the hall fireplace bressummer have been shown to be broadly coeval, with timbers from both dating towards the middle of the first half of the sixteenth century, thus giving support to the stylistic dating previously suggested.

It is unfortunate that 13 of the measured samples are undated, including three site sequences, although these site sequences are poorly replicated with only two samples in each. The ungrouped samples have between 46 (BNK-D08 and BNK-D12) and 100 (BNK-D29) growth rings and, certainly in the case of those samples with less than 60 rings, dating would always be problematic. Even for those samples with higher numbers of growth rings it is well acknowledged that trying to securely date individual samples against the reference chronologies is problematic. This is particularly so in some areas of Devon where more localised networks of reference chronologies are very important in establishing secure dating (Groves 2005; Tyers *et al* forthcoming.

Although undated, by looking at the relative heartwood/sapwood boundary ring positions of the samples in BNKDSQ03–05 (Figs 13–15), it is possible to make some observations about the timbers represented. Two common joists taken from the floor frame of the cross-passage and represented by samples BNK-D03 and BNK-D13 within site sequence BNKDSQ03 can be seen to have been felled one year apart. The two braces of Truss 3, represented by samples BNK-D25 and BNK-D26 in site sequence BNKDSQ05 are also likely to have been felled at the same time. The heartwood/sapwood boundary rings of the other two joists from the cross-passage floor, samples BNK-D01 and BNK-D02, are *c* 25 years apart, making it just about possible that they were felled in the same year, if one had the maximum number of sapwood rings and the other the minimum, however, it is also possible that they were felled some years apart. It is not possible to say whether all six timbers are contemporary or represent two or more separate felling events.

The sites against which site sequence BNKDSQ01 shows similarity are almost exclusively located in Devon (Table 2), mostly mid-Devon, demonstrating the woodland source for the timber is likely to be relatively local. By the time the timber for the doorway and fireplace bressummer is cut it may be that a woodland source located slightly further afield has been utilised as reference chronologies from Devon are less well represented (Table 3). This could, however, be due to the network of reference chronologies in the immediate vicinity being less well replicated and it should be noted that sites in Devon at this period, surprisingly frequently, show strong similarities with sites in Yorkshire.

The successful dating of BNKDSQ01 combined with other relatively recent enhancements to this localised network of reference chronologies spanning the late-thirteenth to early fifteenth centuries for this part of Devon has allowed the secure dating of two previously undated groups of timber from Thorverton and Crediton (Tyers *et al* forthcoming). This again emphasises the need for highly localised networks of reference chronologies in some areas of both this county and others where successful dendrochronology has proven more challenging.

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TABLES

Table 1: Details of tree-ring series from Bunksland Farmhouse, East Anstey, Devon

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Ground-floor timbers						
Cross-passage						
BNK-D01	Ceiling joist 2	90	h/s	----	----	----
BNK-D02	Ceiling joist 4	53	08	----	----	----
BNK-D03	Ceiling joist 6	96	26C	----	----	----
BNK-D13	North-south ceiling beam	86	25C	----	-----	----
BNK-D04	Doorframe into living room – north jamb	64	--	1413	----	1476
BNK-D05	Doorframe into living room – south jamb	109	04	1388	1492	1496
BNK-D06	Doorframe into living room – door head	50	--	1386	----	1435
Hall (present living room)						
BNK-D07	Fireplace bressummer	134	35	1381	1479	1514
BNK-D08	Fireplace – north bracket	46	h/s	----	----	----
BNK-D09	Fireplace – south bracket	59	--	----	----	----
BNK-D10	East ceiling beam	NM	--	----	----	----
BNK-D11	Middle ceiling beam	55	--	----	----	----
BNK-D12	West ceiling beam	46	14	----	----	----
High end (present kitchen)						
BNK-D28	Fireplace bressummer	88	h/s	----	----	----
BNK-D29	Central ceiling beam	100	33C	----	----	----
BNK-D30	Southern ceiling beam	47	h/s	----	----	----
Roof						
BNK-D14	South purlin, truss 1-2	75	12C	1322	1384	1396
BNK-D15	North post, truss 2	NM	--	----	----	----
BNK-D16	North principal rafter, truss 2	48	h/s	1332	1379	1379
BNK-D17	South post, truss 2	55	19	1339	1374	1393
BNK-D18	South principal rafter, truss 2	56	05	1332	1382	1387
BNK-D19	Collar, truss 2	NM	--	----	----	----

BNK-D20	North purlin, truss 2-3	50	14C	1348	1383	1397
BNK-D21	South purlin, truss 2-3	62	18C	1336	1379	1397
BNK-D22	South principal rafter, truss 3	69	21C	1329	1376	1397
BNK-D23	Crown post, truss 3	56	h/s	1325	1380	1380
BNK-D24	Collar, truss 3	48	04	1343	1386	1390
BNK-D25	North brace, truss 3	43	04	----	----	---
BNK-D26	South brace, truss 3	52	12	----	----	----
BNK-D27	North upper purlin, west end – truss 3	47	13C	1351	1384	1397

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 BNKDSQ01 and example reference chronologies when the first ring date is AD 1322 and the last-measured ring date is AD 1397

Site reference	*t* – value	Span of chronology	Reference
21 The Mint, Exeter, Devon	8.0	AD 1261–1414	Nayling 2001
Cleavanger, Nymet Roland, Devon	6.8	AD 1301–1395	Groves 2005
Traymill, Thorverton, Devon	5.5	AD 1341–1404	Tyers *et al* forthcoming
Holy Cross Church, Crediton, Devon	5.3	AD 1311–1430	Tyers *et al* forthcoming
Yeo Barton, Mariansleigh, Devon	5.2	AD 1283–1389	Groves 2005
South Yarde, Rose Ash, Devon	5.2	AD 1309–1447	Groves 1993
West End Farm, Pembridge, Herefordshire	5.1	AD 1322–1424	Tyers 2003
St Nectans Church, Hartland, Devon	4.8	AD 1203–1452	Arnold and Howard 2013
46 High Street, Exeter, Devon	4.7	AD 1309–1491	Arnold and Howard 2009
1 Glebe Cottages, Drewsteignton, Devon	4.5	AD 1268–1393	Tyers 2008

Table 3: Results of the cross-matching of site sequence BNKDSQ02 and example reference chronologies when the first ring date is AD 1381 and the last-measured ring date is AD 1514

Site reference	*t* – value	Span of chronology	Reference
Church of St Ildierna, Lansallos, Cornwall	6.6	AD 1355–1514	Arnold and Howard 2006
First White Cloth Hall, Leeds, West Yorkshire	6.6	AD 1366–1476	Arnold *et al* 2019
Townsend Farmhouse barn, Stockland, Devon	6.4	AD 1387–1478	Tyers and Groves 2003
Horbury Hall, Wakefield, West Yorkshire	6.2	AD 1368–1473	Howard *et al* 1992
New House, Moccas, Herefordshire	6.1	AD 1350–1584	Arnold and Howard 2011
Court House, Shelsley Walsh, Worcestershire	5.9	AD 1387–1575	Arnold *et al* 2008
Exe Bridge, Exeter, Devon	5.8	AD 1335–1506	Tyers forthcoming
Ightfield Hall barn, Shropshire	5.7	AD 1341–1566	Groves 1997
Foresters Lodge, Upper Millichope, Shropshire	5.7	AD 1352–1450	Miles *et al* 1995
South Yarde, Rose Ash, Devon	5.2	AD 1309–1447	Groves 1993

FIGURES

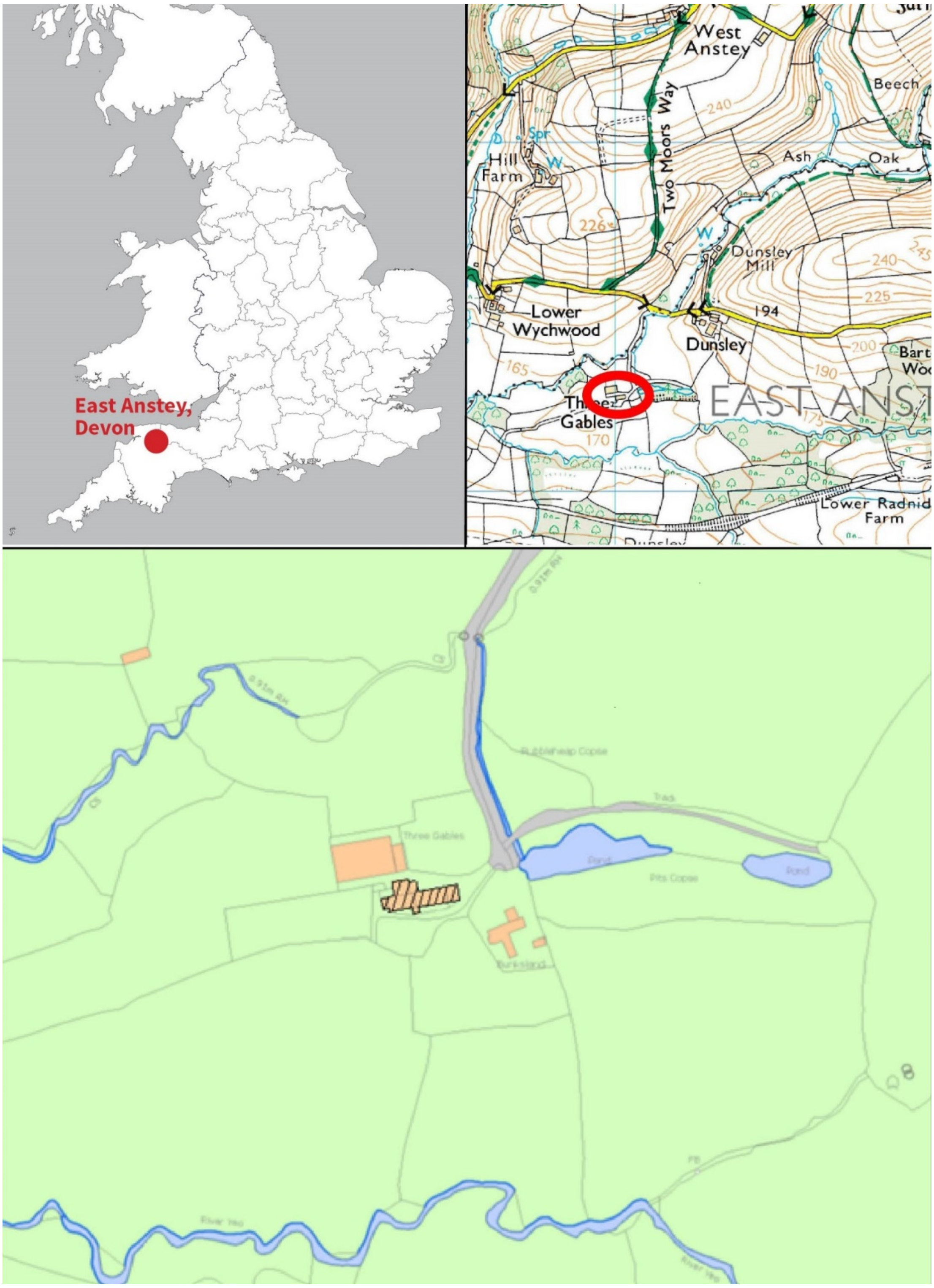

Figure 1: Map to show the location of East Anstey in Devon. Top right: East Anstey circled; Scale: 1:5000. Bottom: Bunksland Farmhouse hashed; Scale 1:2200. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England

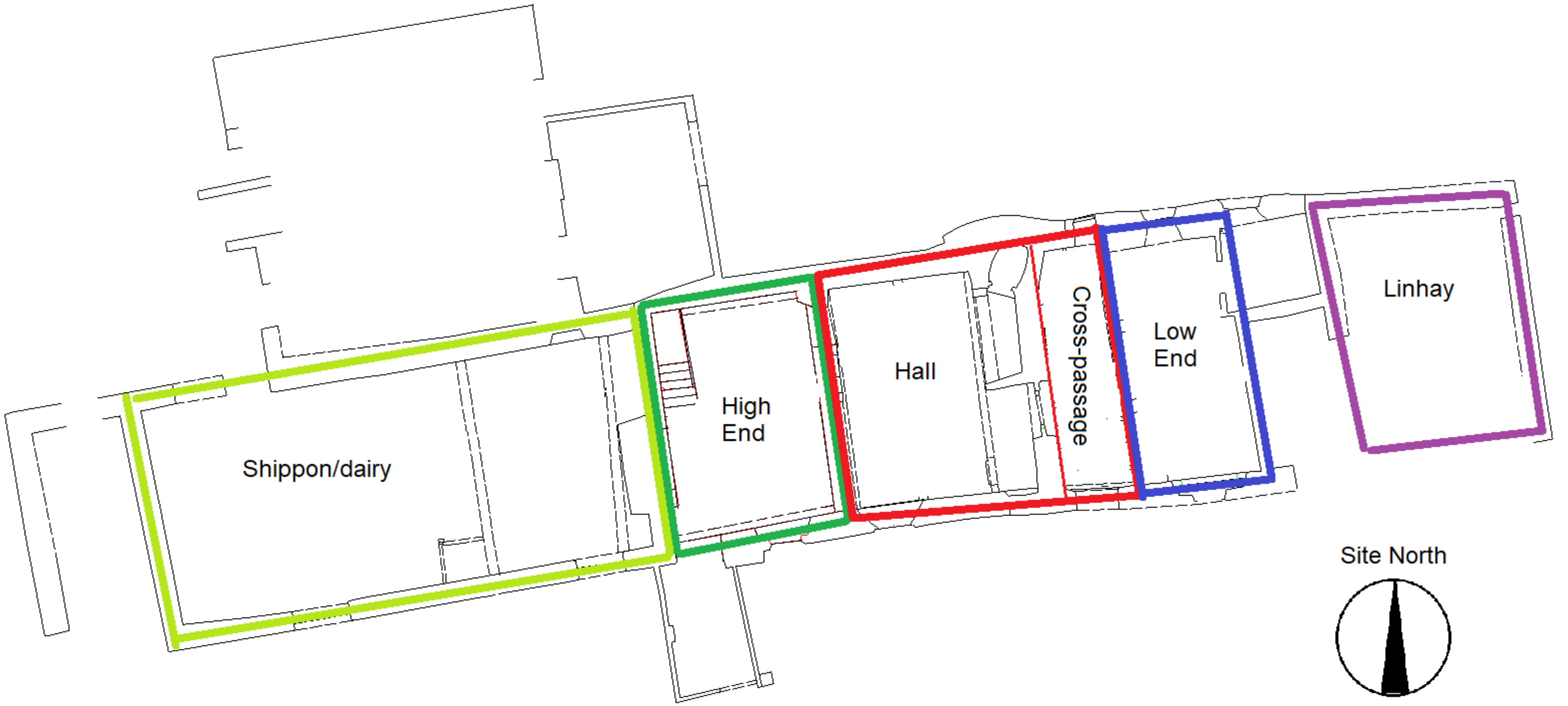

Figure 2: Plan showing the different areas of Bunksland Farmhouse (after Lane, Bayer, and Roethe. Historic England)

Figure 3: Truss 3, photograph taken from the east (Alison Arnold)

Figure 4: Truss 2, with purlins and surviving windbraces, photograph taken from the north-west (Alison Arnold)

Figure 5: High end (present kitchen) ceiling, photograph taken from the north (Alison Arnold)

Figure 6: Hall (present living room) fireplace, showing the location of sampled timbers BNK-D07–09, photograph taken from the south-west (Alison Arnold)


Figure 7: The doorway from the cross-passage into the hall, photograph taken from the east (Alison Arnold)


Figure 8: High end (present kitchen) fireplace bressummer, photograph taken from the east (Alison Arnold)

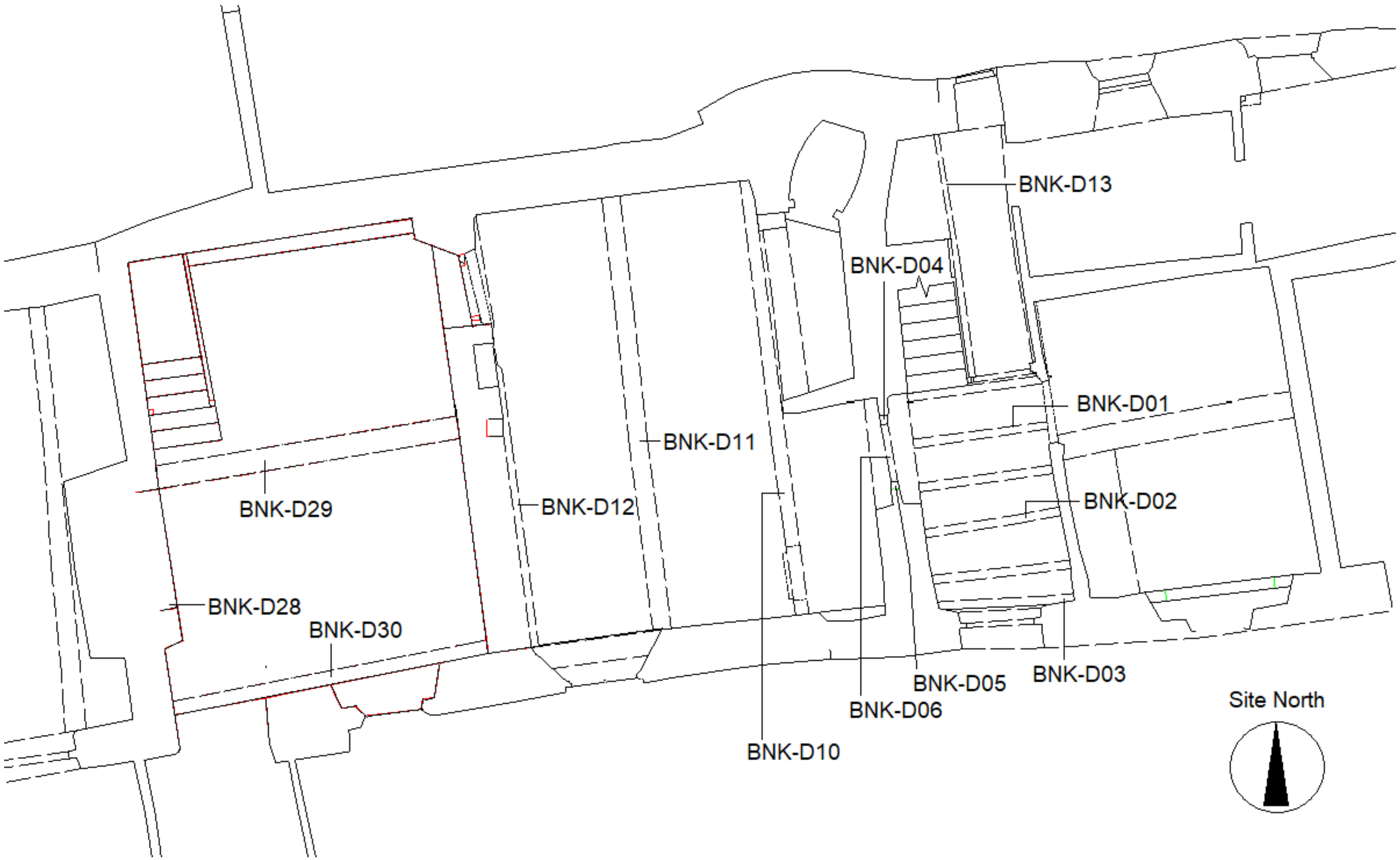

Figure 9: Ground-floor plan, showing the location of sampled timbers BNK-D01–07, BNK-D10–13, and BNK-D28–30 (after Lane, Bayer, and Roethe, Historic England)

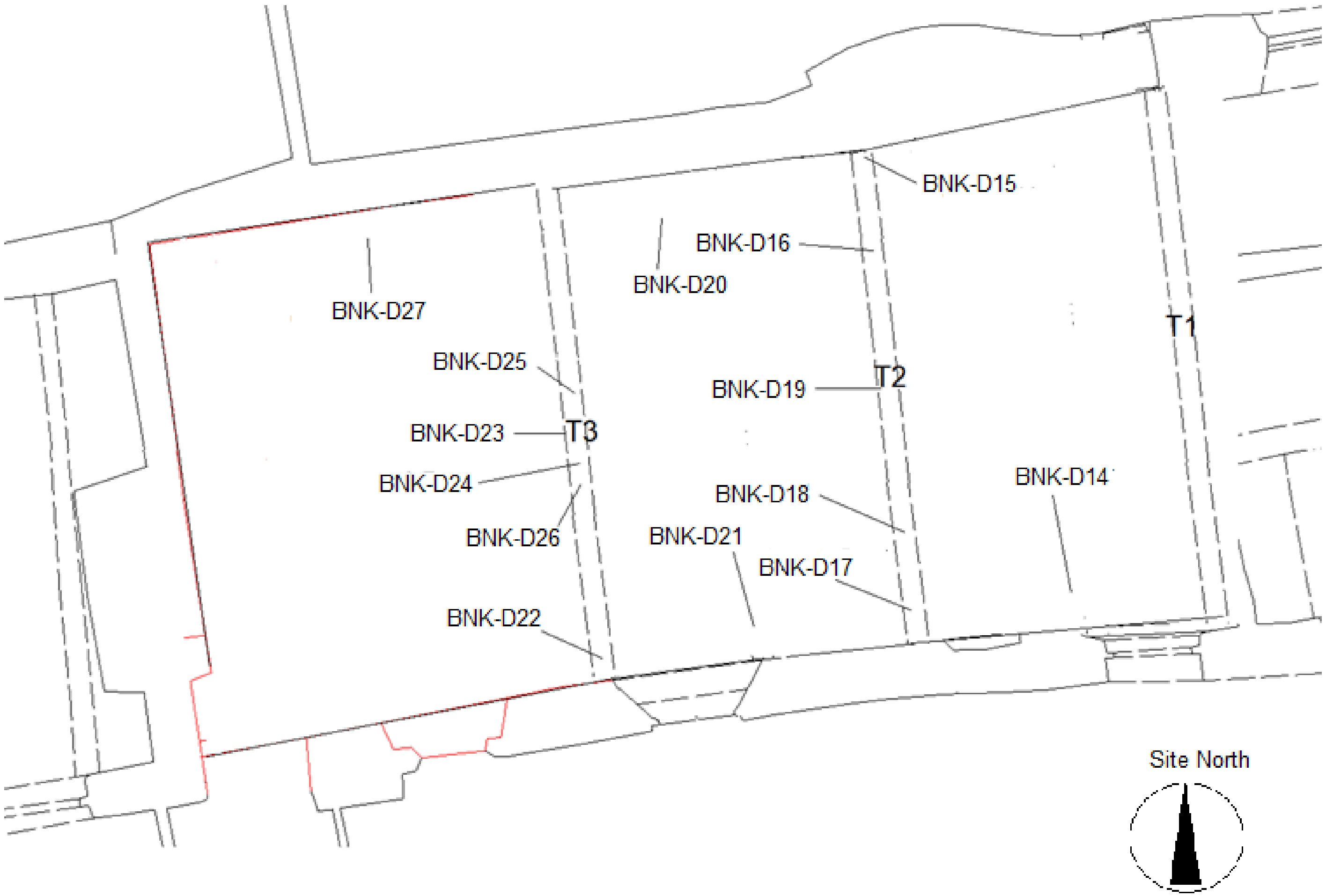

Figure 10: Representative first-floor plan, showing the location of sampled timbers BNK-D14–27 (after Lane, Bayer, and Roethe, Historic England)

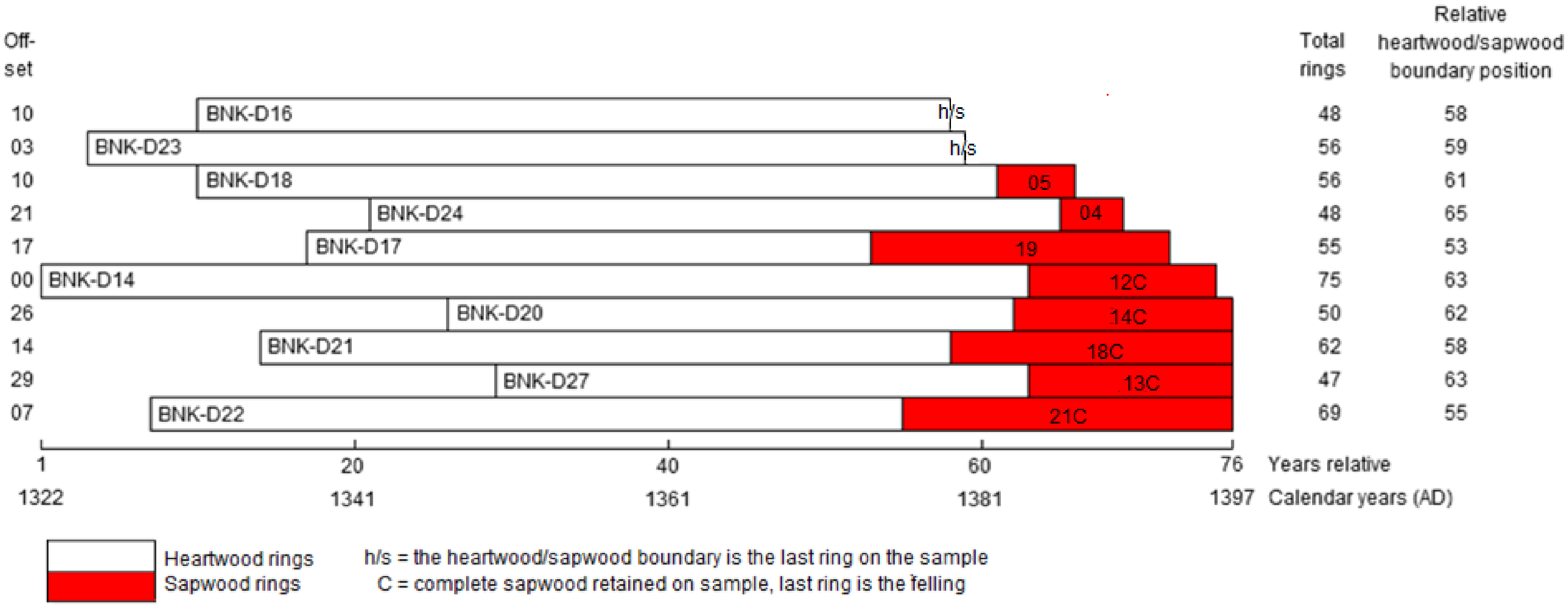

Figure 11: Bar diagram of samples in site sequence BNKDSQ01

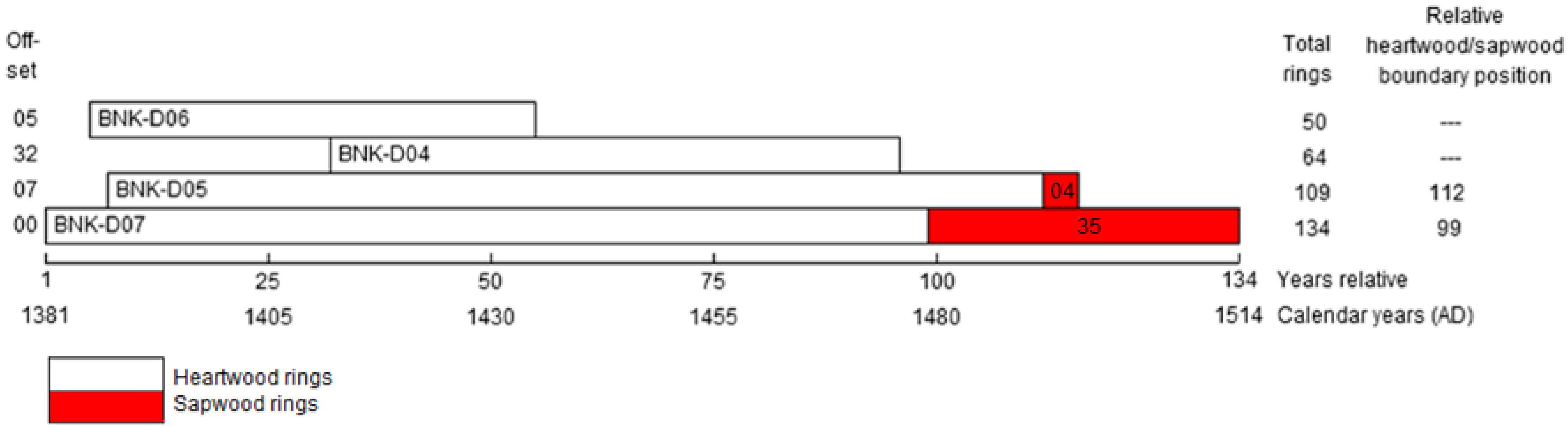

Figure 12: Bar diagram of samples in site sequence BNKDSQ02

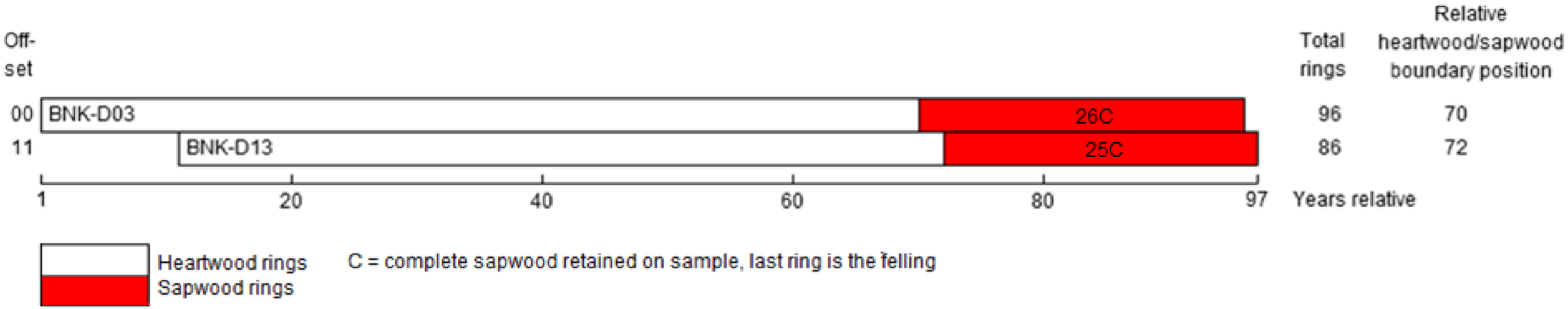

Figure 13: Bar diagram of samples in undated site sequence BNKDSQ03

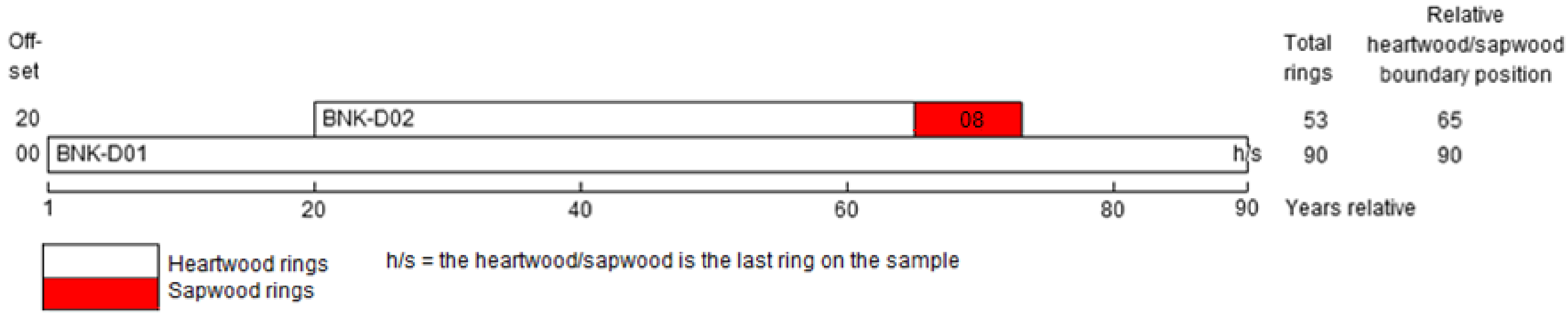

Figure 14: Bar diagram of samples in undated site sequence BNKDSQ04

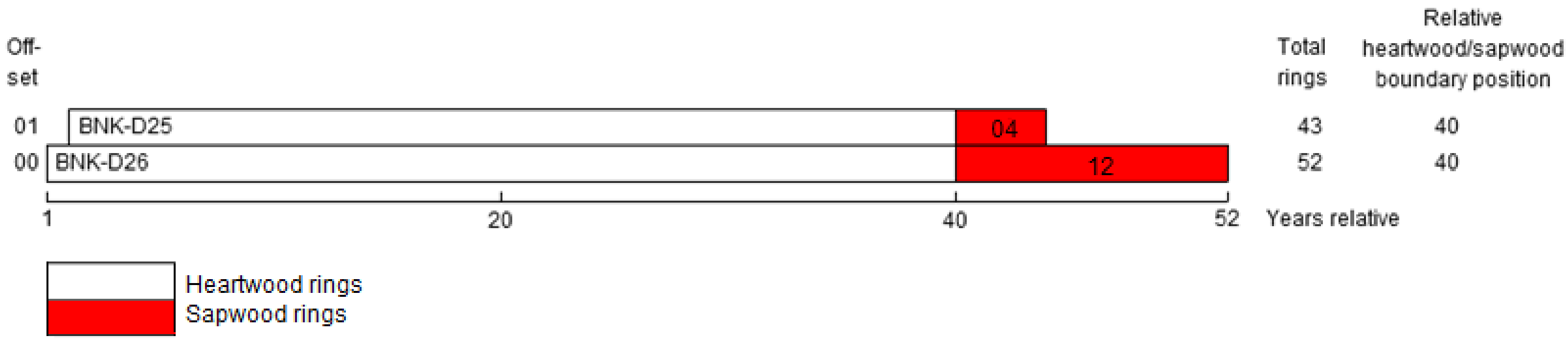

Figure 15: Bar diagram of samples in undated site sequence BNKDSQ05

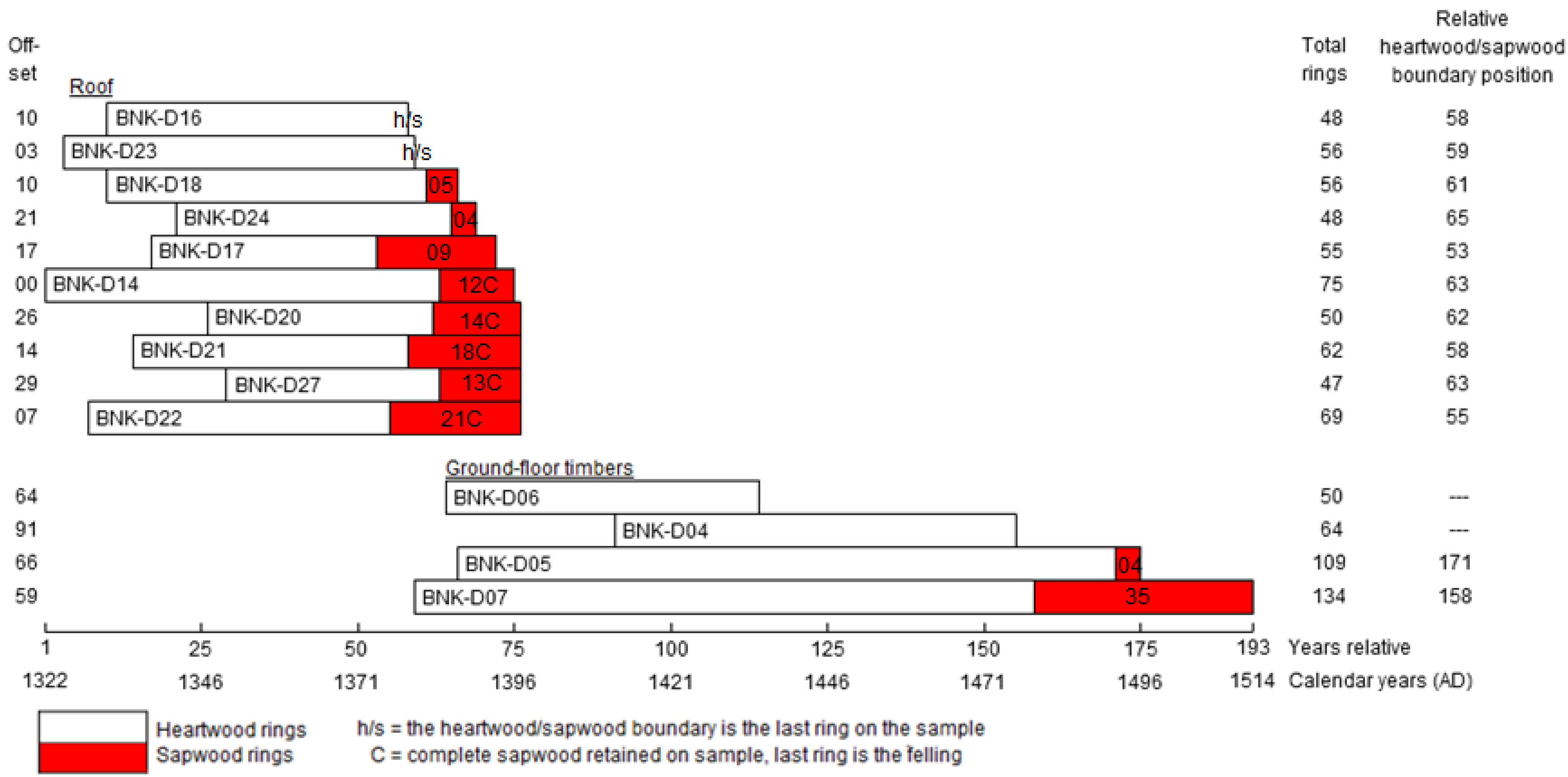

Figure 16: Bar diagram of all dated samples, sorted by area

DATA OF MEASURED SAMPLES

BNK-D01A 90
157 189 199 247 189 163 233 109 44 40 57 94 100 47 92 127 139 167 131 216
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174 164 204 86 55 53 58

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. Inspecting the Building and Sampling the Timbers.

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

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

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

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

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

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

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

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

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

2. *Measuring Ring Widths.*

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

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

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

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

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

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

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

4. Estimating the Felling Date.

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

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

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

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

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

5. Estimating the Date of Construction.

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

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

6. Master Chronological Sequences.

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

7. Ring-Width Indices.

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

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

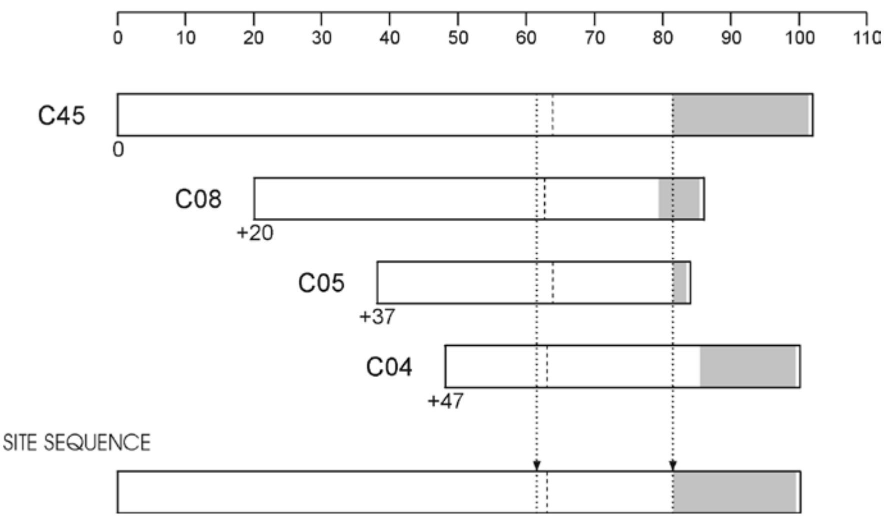


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

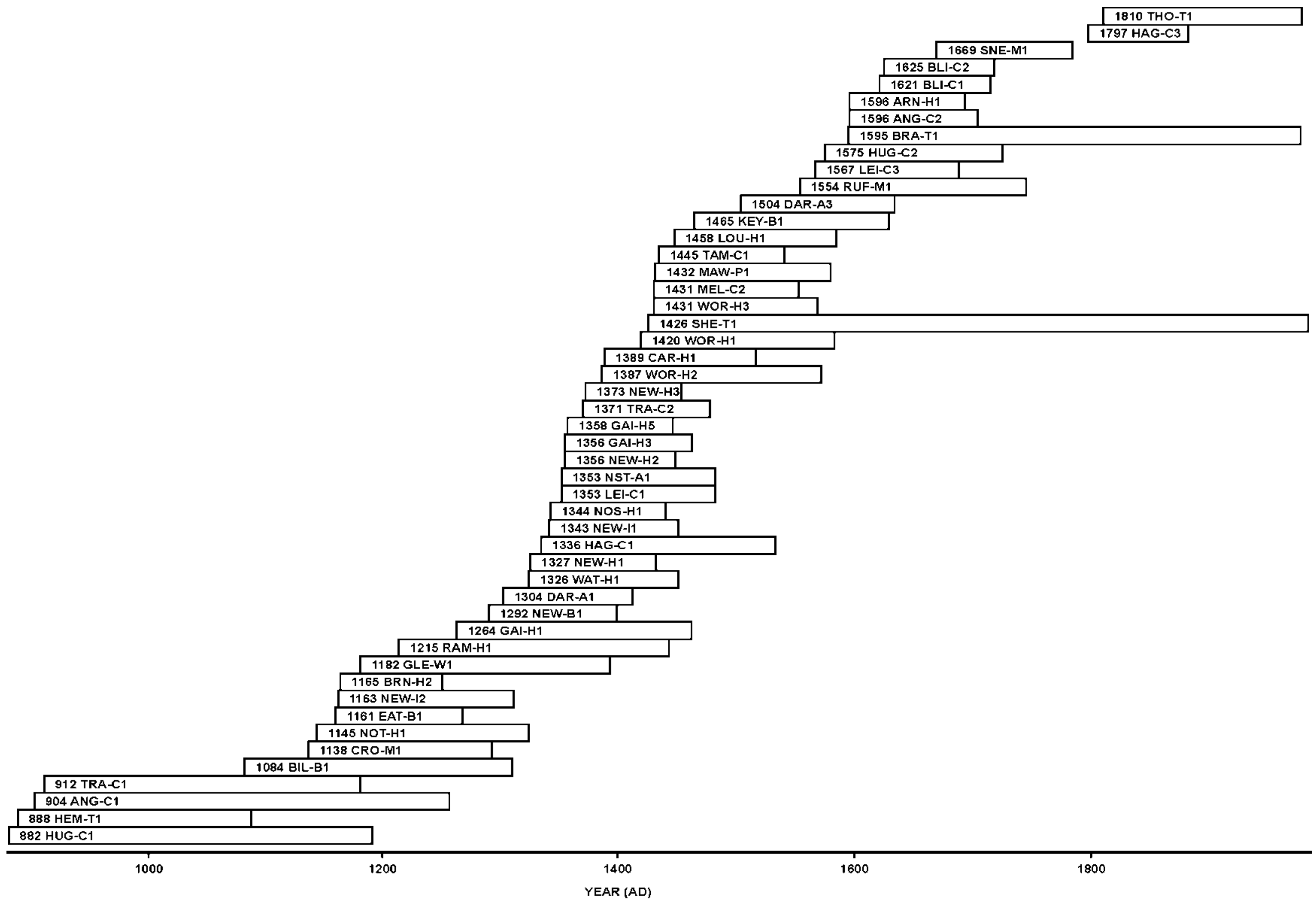
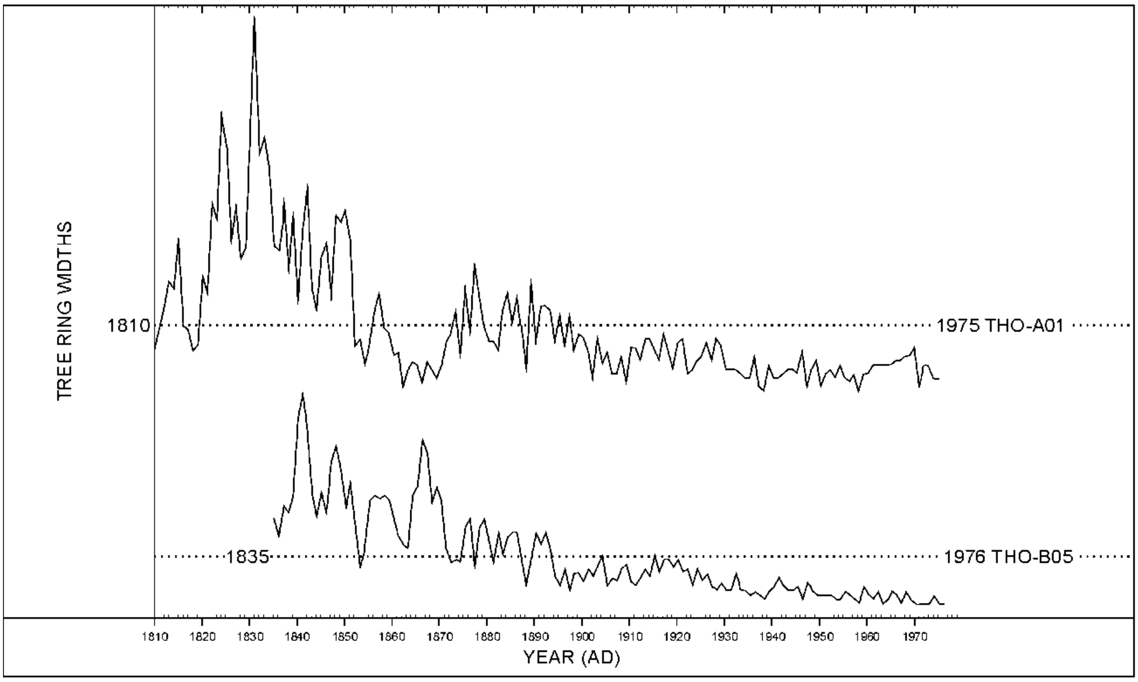


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

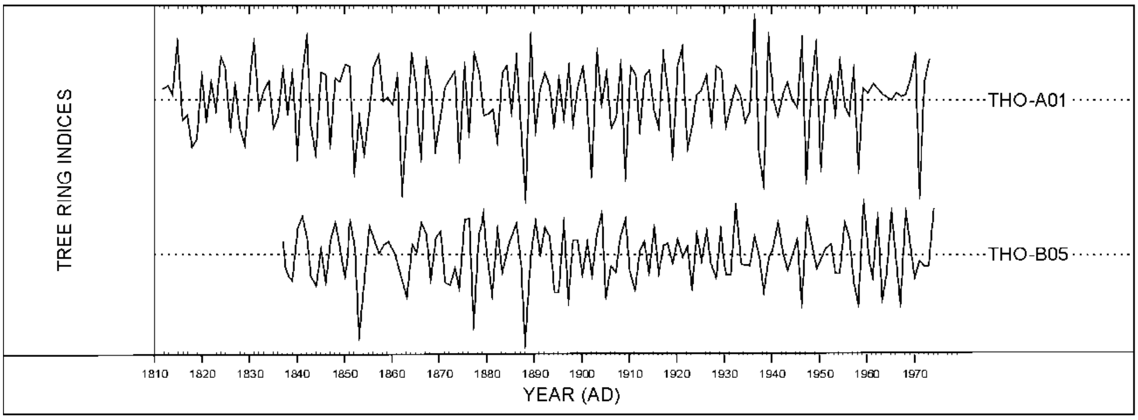


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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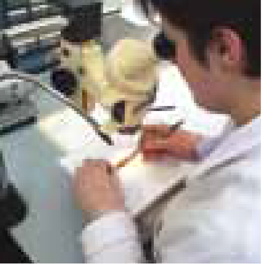
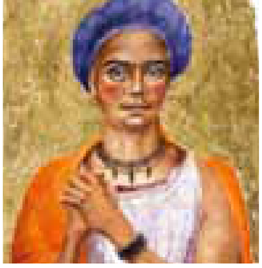


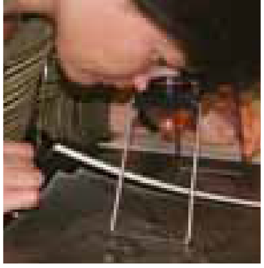


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