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Summary

Fourteen core samples were taken from roof timbers at this building. Of these three were found to be unsuitable for tree-ring dating. Analysis of the remaining 11 samples resulted in the construction of a single dated site sequence and one individually dated sample.

Site sequence WPGASQ04 contains five samples and spans the period AD 1410-1511. Interpretation of the heartwood/sapwood boundary ring dates of these samples suggests a contemporary felling in AD 1512-36 for the five timbers represented.

Sample WPG-A10 was dated individually to the period AD 1386-1449. Without the heartwood/sapwood boundary ring an estimated felling date cannot be calculated for this sample except to say that this would be AD 1465 at the earliest.

A further site sequence, WPGASQ03, containing two samples is undated.

Tree-ring analysis has shown this roof to be constructed primarily from timbers felled in AD 1512-36. However, there is an unconfirmed possibility that at least one timber of the late-fifteenth century has been incorporated into this roof.

Keywords

Dendrochronology
Standing Building

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Introduction

Wetheral Priory, Wetheral (Fig 1; NY 468542) is situated next to a narrow lane, south of the village, and above the river Eden. It was founded by Ranulph Meschin, the first Norman lord of Cumberland, in *c* AD 1106, as a cell of the Abbey of St Mary, in York. It was set up for a prior and 12 Benedictine monks. On its establishment it was dedicated to the Celtic saint, St Constantine, and gifted with the churches of Wetheral and Warwick, and in succeeding years further churches were added to its patronage. It had the coveted right of sanctuary, endowed upon it by Henry I, the limit of which was marked by six boundary crosses. The last prior at Wetheral was Ralf Hartley who signed the deed of surrender of the monastery in AD 1538. After this the priory was dismantled, with its possessions and furnishings being sold in that same year.

All that really remains today of this Benedictine priory is the fine, two-storey gatehouse. Current dating of the gatehouse is based on the style of its masonry mouldings, which puts it in the fifteenth century. Post-dissolution the gatehouse was used as a vicarage in the sixteenth and seventeenth centuries, but after this was used as a hayloft. It was given into the guardianship of the state in AD 1978.

The gate passageway is barrel-vaulted and occupies the northern half of the ground plan. A projection at the north-east corner contains the spiral staircase which continues up to the roof and provides access to the upper floors which were domestic chambers for priory officials (Fig 2). The first floor consists of a single room, with a fireplace in the east wall. It is lit by three windows, a two-light above the entrance arch, and single-lights in the east and south walls. All windows are well moulded, with cusped trefoil heads and external hood-moulds. There are two mural chambers over the entrance arch, with observation openings, one looking towards the north and one to the south. In the south-east corner there is a garderobe (Fig 3). The timbers of the second floor, which were once supported on large stone corbels, have since disappeared. The second-floor chamber would have been very similar to the one below, with the two mural chambers in the west wall, and another garderobe above the first-floor one (Fig 4).

The roof as seen today is not thought to be in its original form, showing signs of having been lowered some 1.3m at a point in the past. The principal rafters have empty mortices and it has been suggested that these would have been for collars, making the primary roof structure A-shaped. The roof is thought to date to c AD 1540. However, this could be simply the date that the roof was lowered, possibly when the gatehouse became the parish vicarage.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage. It was hoped that this would indicate whether the extant roof was constructed *c* AD 1540 and whether it contained earlier timber, potentially reused from the original roof thought to be of fifteenth-century date. If successful this may determine the date when the roof was lowered and also, if earlier timbers are present, then the results may provide precise dating evidence for the construction of the gatehouse on grounds other than by style of its masonry mouldings.

The Laboratory would like to thank Miss Brownrigg, the key holder, for assistance in access and David Sherlock, the English Heritage inspector, for his on-site advice. Carlisle Scaffolding Limited supplied and erected the scaffolding. The above introduction and figures used to illustrate this report are taken from an article written by J K H Martindale (1922).

Sampling

Fourteen core samples were taken from a range of timbers of this roof, from principal rafters, tiebeams, purlins, and the ridge. The common rafters were not sampled as these appeared to be largely softwood replacements. The two sets of short purlins in bay 1 were seen to have a wider ring pattern than the other timbers. The two thought most likely to have sufficient rings for analysis were sampled but these were found to be unsuitable for tree-ring dating (see below). Each sample was given the code WPG-A (for Wetheral, Priory Gatehouse) and numbered 01-14. The position of all samples was noted at the time of sampling and has been marked on Figures 5-7. Further details relating to the samples can be found in Table 1. For the purpose of this report roof trusses have been numbered north to south.

Analysis and Results

At this stage it was noticed that three of the samples (WPG-A12, WPG-A13, and WPG-A14) had too few rings for secure dating, and so they were rejected prior to measurement. The remaining 11 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 were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a least value of t=4.5, six samples had formed three groups.

Firstly, two samples matched each other and site chronology WPGASQ01, a sequence of 95 rings, was constructed containing these samples at the offsets shown in the bar diagram (Fig 8). This site sequence was then compared with a large number of relevant reference chronologies for oak indicating a consistent match when the date of its first ring is AD 1411 and of its last measured ring is AD 1505 (Table 2).

Two further samples matched each other and were combined at the relevant offset positions to form WPGASQ02, a site sequence of 102 rings (Fig 9). This site sequence was again matched against the reference chronologies where it was found to span the period AD 1410-1511 (Table 3).

Finally, two samples grouped and a third site sequence of 87 rings, WPGASQ03, was constructed containing these samples at the relevant offsets

(Fig 10). Attempts to date this site sequence by comparing it against the reference chronologies were unsuccessful and these samples remain undated.

The remaining five samples were then compared individually with the reference chronologies, at which point sample WPG-A03 was found to match at a first-ring date of AD 1429 and a last-ring date of AD 1503 (Table 4), and WPG-A10 at a first-ring date of AD 1386 and a last-ring date of AD 1449 (Table 5).

It was then seen that site sequence WPGASQ01 matched both site sequence WPGASQ02 and sample WPG-A03 at a value of t=4.2, at the offsets indicated by their independent dating. Because of this a fourth site sequence, WPGASQ04, of 102 rings was then constructed containing the two samples from WPGASQ01, the two samples from WPGASQ02, and sample WPG-A03 at the offsets shown in the bar diagram (Fig 11). Matching against the reference chronologies indicate a first-ring date for this site chronology of AD 1410 and a last-ring date of AD 1511 (Table 6).

Interpretation

Analysis of 11 samples taken from roof timbers of this building has resulted in the successful dating of six of them.

Site sequence WPGASQ04 contains five samples and spans the period AD 1410-1511. All of the samples have the heartwood/sapwood boundary ring which are broadly contemporary (ranging from AD 1489-1503), suggestive of a single felling. The average heartwood/sapwood ring date is AD 1496 which, allowing for sample WPG-A08 having a last measured ring date of AD 1511 with incomplete sapwood, calculates to a felling date range of AD 1512-36 for the five timbers represented (four principal rafters and one tiebeam).

Sample WPG-A10 was dated individually to the period AD 1386-1449. This sample does not have the heartwood/sapwood boundary ring, and so a felling date range cannot be calculated for it except to say that at the earliest this would be estimated to be AD 1465. It is possible therefore that this timber was also felled in 1512-36, but had been more heavily trimmed during conversion or, alternatively it could represent a separate, earlier felling.

All felling date ranges have been calculated using the estimate that 95% of mature oak trees in this area have between 15-40 sapwood rings.

Discussion

The dendrochronological analysis has identified at least one, but possibly two, fellings associated with the timbers of this roof. Four principal rafters and one tiebeam are now known to have been felled in AD 1512-36. A purlin felled some time after AD 1464 might represent an earlier felling, however, without the heartwood/sapwood boundary ring this cannot be positively confirmed and it remains a possibility that it is contemporary with the early sixteenth-century felling.

The gatehouse itself had previously been dated on stylistic grounds to the fifteenth century with the present roof thought to be later, dating to *c* AD 1540, ie, to the dissolution. Because the principal rafters have empty mortices it had been suggested that these timbers were from the original fifteenth-century roof, with the tiebeams relating to the lowering of it some time later. The dating of four of these principal rafters and one of the tiebeams to a contemporary felling in AD 1512-36 (ie, pre-dissolution) shows this not to be the case.

The tree-ring analysis has shown at least four of the principal rafters and one of the tiebeams to have a pre-dissolution, rather than the expected fifteenth century (if reused from the original roof) or post-dissolution, date. These results are further complicated by the principal rafters having redundant mortices. Unless these empty mortices simply indicate a change in plan during construction, in which case it is suggested that the roof was constructed in or soon after felling of the timbers in AD 1512-36, the implication is that these principal rafters are reused, although not from the original fifteenth-century roof as previously thought but rather from an early sixteenth-century roof

This raises the possibility that the fifteenth-century roof was replaced utilising timbers reused from an early sixteenth-century roof. This could have been in *c* AD 1540 but this work could also have taken place at some other time. Alternatively, it could be that the original roof was replaced in or soon after felling of the timbers in AD 1512-36; this roof then being lowered at a later date, thereby explaining the redundant mortices.

The question had been raised as to whether any of the earlier, fifteenth century timbers of the primary roof had been incorporated in the present roof. The dating of a single purlin, possibly to the second half of the fifteenth century, may be evidence of the use of reused timber, perhaps from the original roof. However, in the absence of any sapwood this cannot be confirmed by dendrochronology and, with no obvious evidence for reuse noted on the timber, this is speculation at present.

It was unfortunate that none of the four short purlins were suitable for tree-ring analysis and the date of these timbers is still unknown. The fact that the second long purlin (WPG-A11) could not be successfully dated is most likely due to its short ring-width sequence, only 55 rings. The inability to date reference chronology WPGASQ03 could be due to slight banding seen on the samples. This might suggest some disruption in the usual growth pattern experienced by the tree/s these came from, which would interfere both with the matching against the other samples from the site and with the matching against the reference chronologies. Two of the tiebeams are still undated. One of these, sample WPG-A02, had been identified as probably later than the other two as it is not arched in the same way. When sampled it was seen to display signs of mechanical sawing, putting it in the eighteenth century at the earliest. Lack of reference chronologies for this region in the later period could explain the inability to date this single sample. Sample WPG-A01, taken from the tiebeam of truss 1 has 80 rings, sufficient rings for satisfactory analysis and shows no unusual characteristics in its growth regime. The success rate of suitable samples dated from buildings is about 72%. Sample WPG-A01 is therefore simply one of the percentage of apparently suitable samples that does not date, and not necessarily of a different date.

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Table 1: Details of tree-ring samples from Wetheral Priory Gatehouse, Wetheral

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
WPG-A01	Tiebeam, truss 1	80	04	----	----	----
WPG-A02	Tiebeam, truss 2	122	30C	----	----	----
WPG-A03	Tiebeam, truss 3	75	h/s	1429	1503	1503
WPG-A04	East principal rafter, truss 1	94	03	1411	1501	1504
WPG-A05	West principal rafter, truss 1	91	07	1415	1498	1505
WPG-A06	East principal rafter, truss 2	54	h/s	1437	1490	1490
WPG-A07	West principal rafter, truss 2	87	--	----	----	----
WPG-A08	East principal rafter, truss 3	102	22c	1410	1489	1511
WPG-A09	West principal rafter, truss 3	70	--	----	----	----
WPG-A10	East purlin, truss 1-3	64	--	1386	----	1449
WPG-A11	West purlin, truss 1-3	55	--	----	----	----
WPG-A12	West lower (short) purlin N-truss 1	NM	--	----	----	----
WPG-A13	West upper (short) purlin, N-truss 1	NM	--	----	----	----
WPG-A14	Ridge, S-truss 2	NM	--	----	----	----

*NM = not measured
h/s = the heartwood/sapwood boundary is the last ring on the sample
c = complete sapwood on timber, all or part lost in sampling
C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence WPGASQ01 and relevant reference chronologies when the first-ring date is AD 1411 and the last-ring date is AD 1505

Reference chronology	*t*-value	Span of chronology	Reference
England	5.2	AD 404-1981	Baillie and Pilcher 1982 unpubl
East Midlands	4.5	AD 882-1982	Laxton and Litton 1988
Speke Hall, The Walk, Speke, Merseyside	5.9	AD 1387-1574	Howard *et al* 1992
Saltby Church (bellframe), Leics	5.0	AD 1446-1625	Howard *et al* 1995
Nether Levens Hall, Kendal, Cumbria	4.8	AD 1395-1541	Howard *et al* 1991
Melbourne Church, Derbys	4.7	AD 1431-1559	Laxton and Litton 1988
Hardwick Old Hall, Derbys	4.5	AD 1375-1590	Howard *et al* 2002a
Combermere Abbey, Cheshire	4.4	AD 1363-1564	Howard *et al* 2003

Table 3: Results of the cross-matching of site sequence WPGASQ02 and relevant reference chronologies when the first-ring date is AD 1411 and the last-ring date is AD 1505

Reference chronology	*t*-value	Span of chronology	Reference
Belfast	5.3	AD 1001-1970	Baillie 1977
England	4.6	AD 404-1981	Baillie and Pilcher 1982 unpubl
Combermere Abbey, Cheshire	4.7	AD 1363-1564	Howard *et al* 2003
Sherwood Trees	4.7	AD 1426-1981	Laxton and Litton 1988
Speke Hall, The Walk, Speke, Merseyside	4.6	AD 1387-1574	Howard *et al* 1992
Gotham Manor, Gotham, Notts	4.6	AD 1410-1474	Howard *et al* 1991 unpubl
Forbury Chapel, Herefordshire	4.6	AD 1432-1520	Arnold *et al* 2003
Old Durham Farm, Durham, Tyne and Wear	4.5	AD 1390-1619	Howard *et al* 1995
Old Rectory, Cossington, Leics	4.5	AD 1375-1526	Howard *et al* 1992

Table 4: Results of the cross-matching of sample WPG-A03 and relevant reference chronologies when the first-ring date is AD 1386 and the last-ring date is AD 1449

Reference chronology	*t*-value	Span of chronology	Reference
England	4.3	AD 404-1981	Baillie and Pilcher 1982 unpubl
Seaton Holme, Easington, Durham	6.7	AD 1375-1489	Howard *et al* 1988 unpubl
Manor House, Long Clawson, Leics	6.3	AD 1485-1602	Howard *et al* 1991
Nether Levens Hall, Kendal, Cumbria	5.4	AD 1395-1541	Howard *et al* 1991
Trinity House (rigging loft), Newcastle upon Tyne	5.0	AD 1397-1524	Howard *et al* 2002b
Kepier Hospital, Durham, Tyne and Wear	4.8	AD 1304-1522	Howard *et al* 1996
Hallgarth Manor Cottages, Hallgarth, Pittington, Co Durham	4.7	AD 1336-1624	Howard *et al* 2001

Table 5: Results of the cross-matching of sample WPG-A10 and relevant reference chronologies when the first-ring date is AD 1386 and the last-ring date is AD 1449

Reference chronology	*t*-value	Span of chronology	Reference
England	7.3	AD 404-1981	Baillie and Pilcher 1982 unpubl
Belfast	5.6	AD 1001-1970	Baillie 1977
Horbury Hall, Horbury, Wakefield, West Yorks	7.0	AD 1368-1473	Howard *et al* 1992
Nether Levens Hall, Kendal, Cumbria	6.6	AD 1395-1541	Howard *et al* 1991
Speke Hall, The Walk, Speke, Merseyside	6.0	AD 1387-1574	Howard *et al* 1992
1 Vicars' Close, Lichfield, Staffs	5.7	AD 1359-1446	Arnold *et al* 2002
Seaton Holme, Easington, Durham	5.6	AD 1375-1489	Howard *et al* 1988 unpubl
Hall Broom Farm, Dungworth, Bradfield, Derbys	5.5	AD 1382-1495	Howard *et al* 1993

Table 6: Results of the cross-matching of site sequence WPGASQ04 and relevant reference chronologies when the first-ring date is AD 1377 and the last ring date is AD 1511

Reference chronology	*t*-value	Span of chronology	Reference
England	6.9	AD 404-1981	Baillie and Pilcher 1982 unpubl
Belfast	6.6	AD 1001-1970	Baillie 1977
Speke Hall, The Walk, Speke, Merseyside	6.8	AD 1387-1574	Howard *et al* 1992
Nether Levens Hall, Kendal, Cumbria	6.2	AD 1395-1541	Howard *et al* 1991
Seaton Holme, Easington, Durham	6.1	AD 1375-1489	Howard *et al* 1988 unpubl
Ordsall Hall, Taylorson Street, Salford	5.8	AD 1385-1512	Howard *et al* 1994
Hall Broom Farm, Dungworth, Bradfield, Derbys	5.4	AD 1382-1495	Howard *et al* 1993
Combermere Abbey, Cheshire	5.4	AD 1363-1564	Howard *et al* 2003

Figure 1: Map to show the location of Wetheral Priory Gatehouse, Wetheral

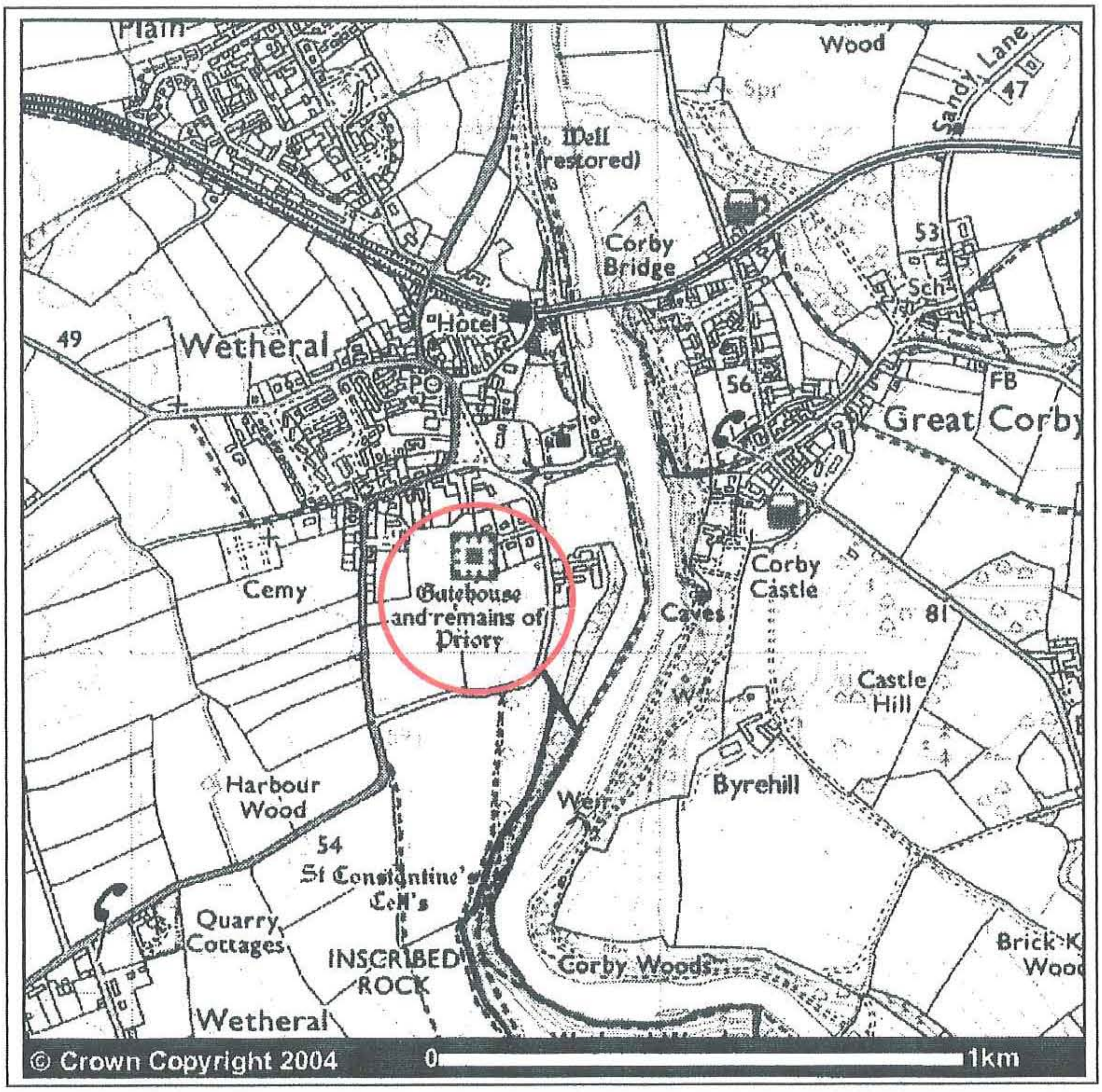


Figure 2: Ground-floor plan (after Martindale 1922)

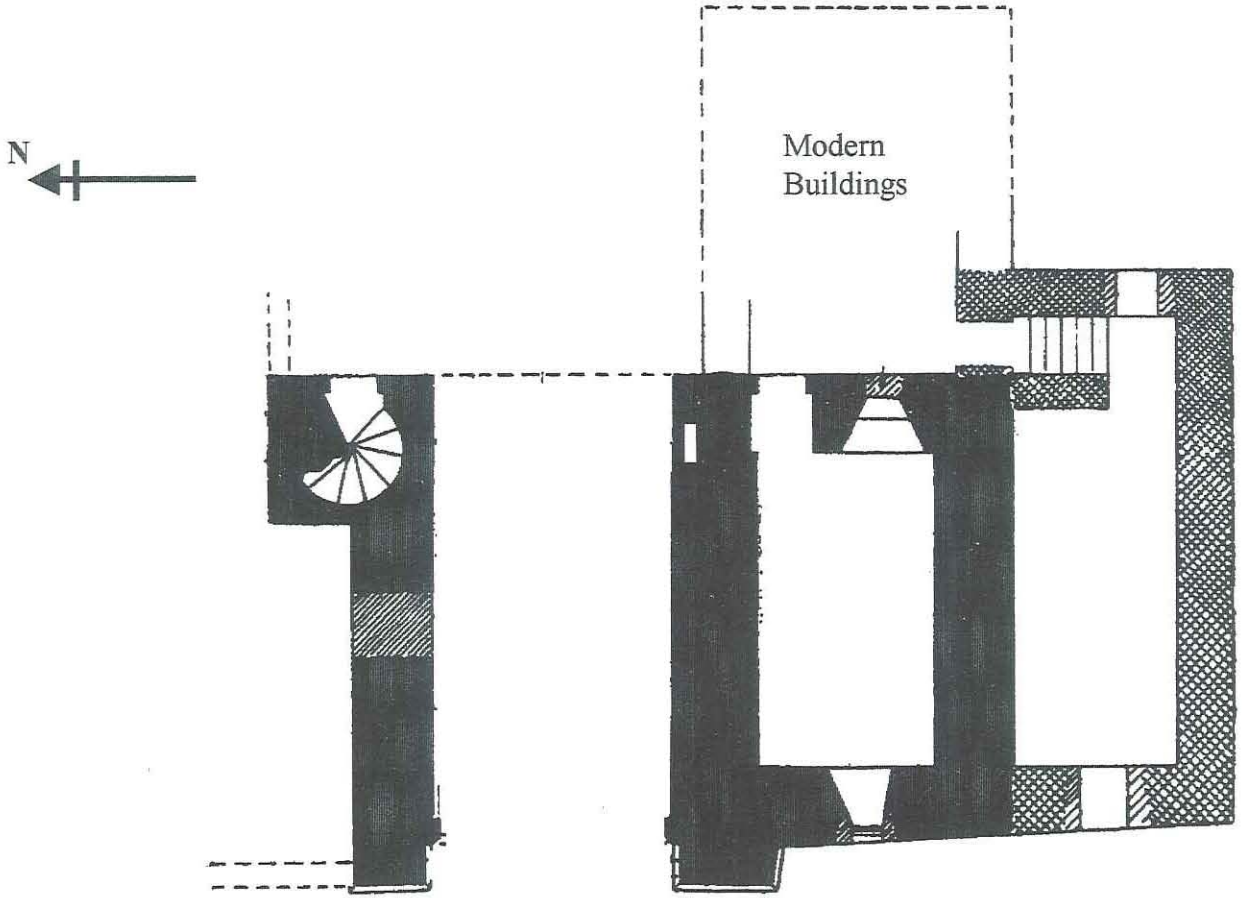


Figure 3: First-floor plan (after Martindale 1922)

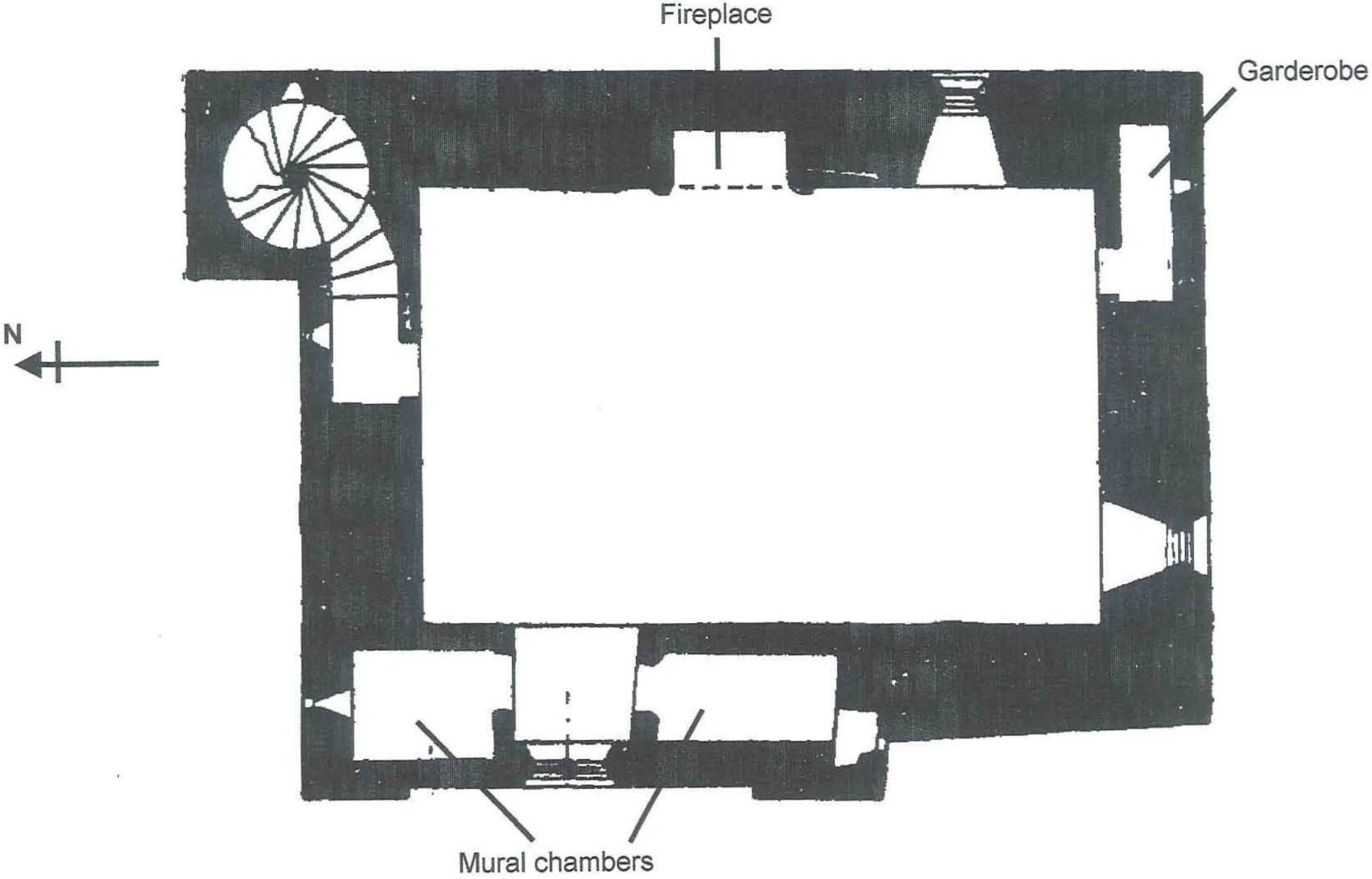


Figure 4: Second-floor plan, showing the roof trusses (after Martindale 1922)

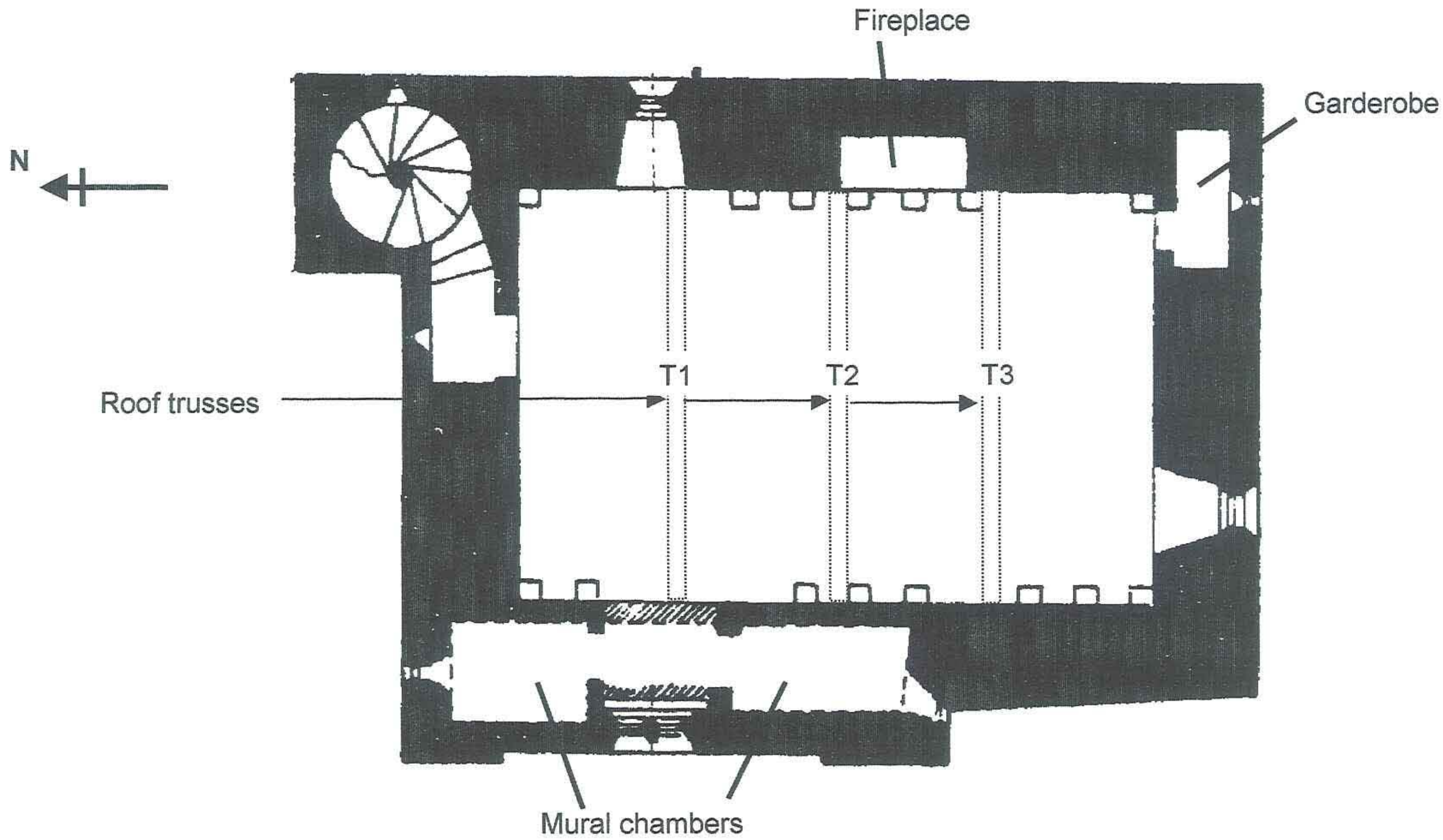


Figure 5: Sketch of Truss 1 (looking north), showing the location of samples WPG-A01, WPG-A04-05, and WPG-A12-13

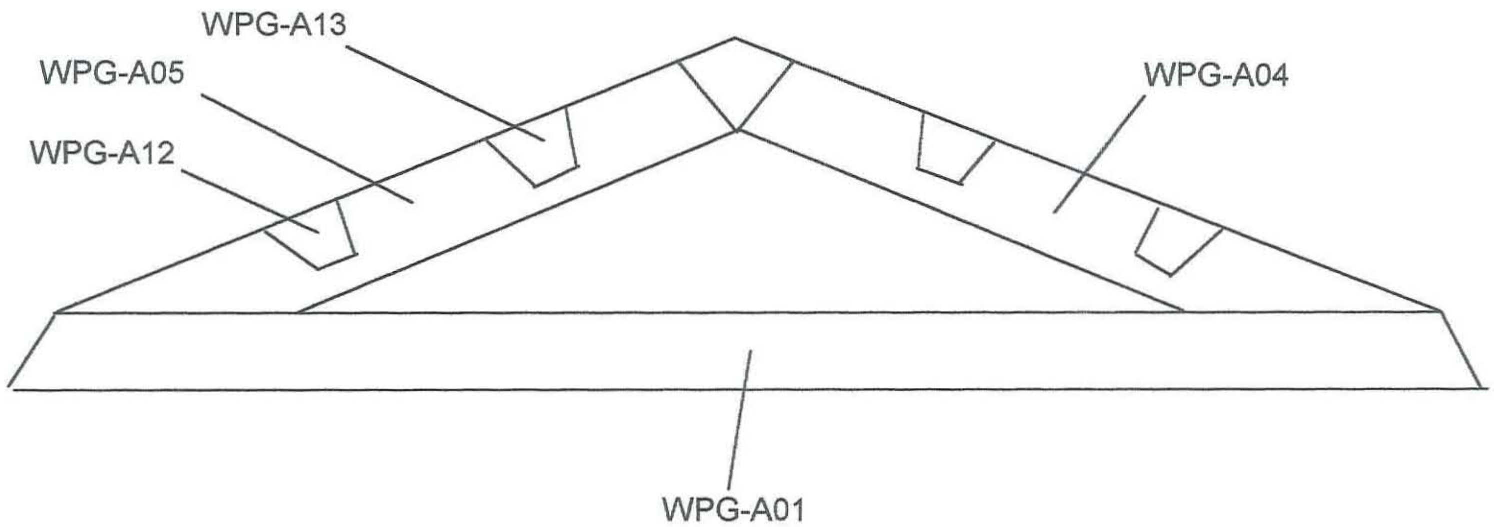


Figure 6: Sketch of Truss 2 (looking north), showing the location of samples WPG-A02, and WPG-A06-07

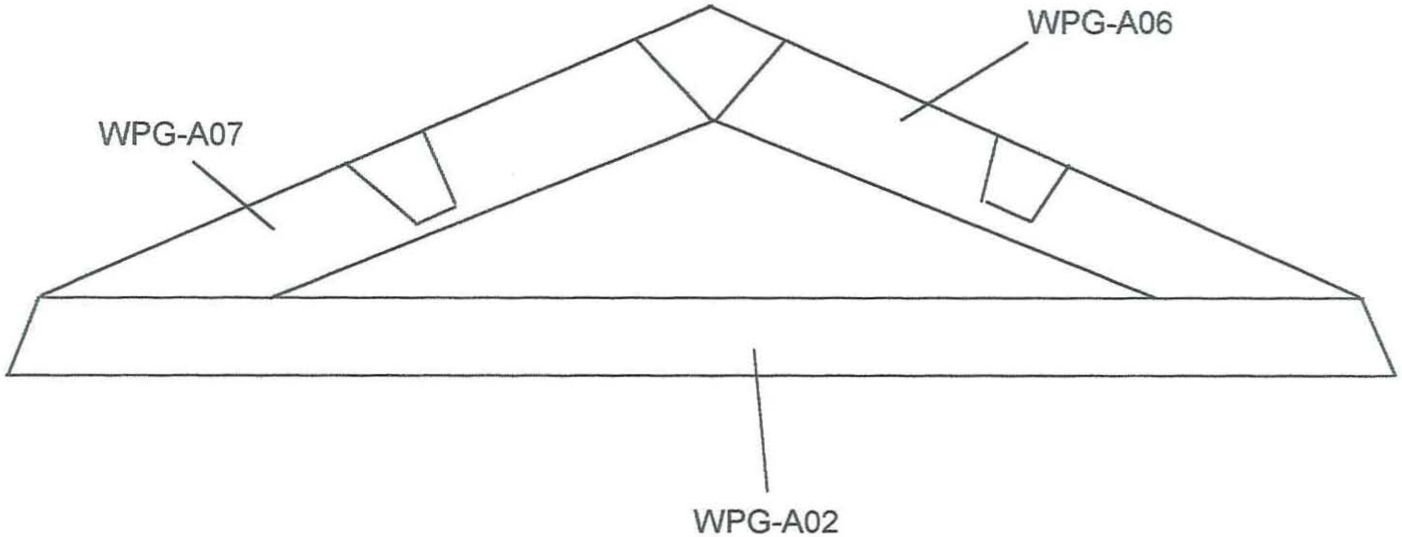


Figure 7: Sketch of Truss 3 (looking north), showing the location of samples WPG-A03, WPG-A08-11, and WPG-A14

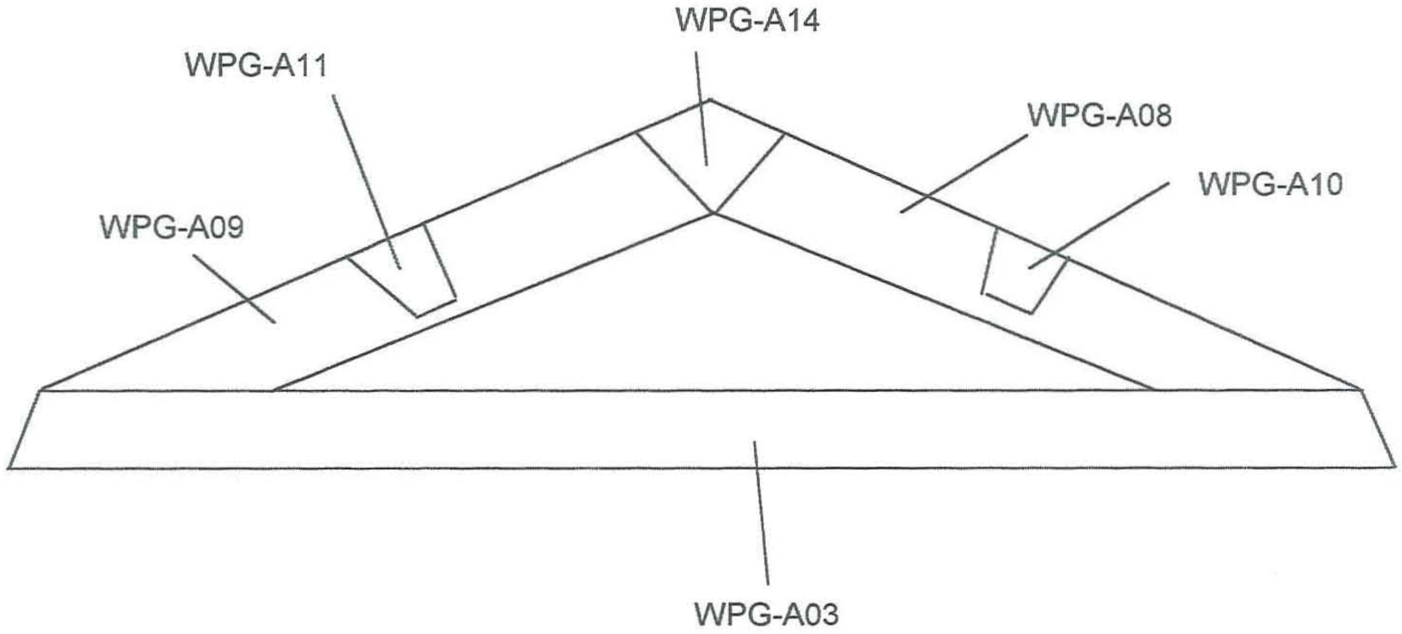


Figure 8: Bar diagram of samples in site sequence WPGASQ01

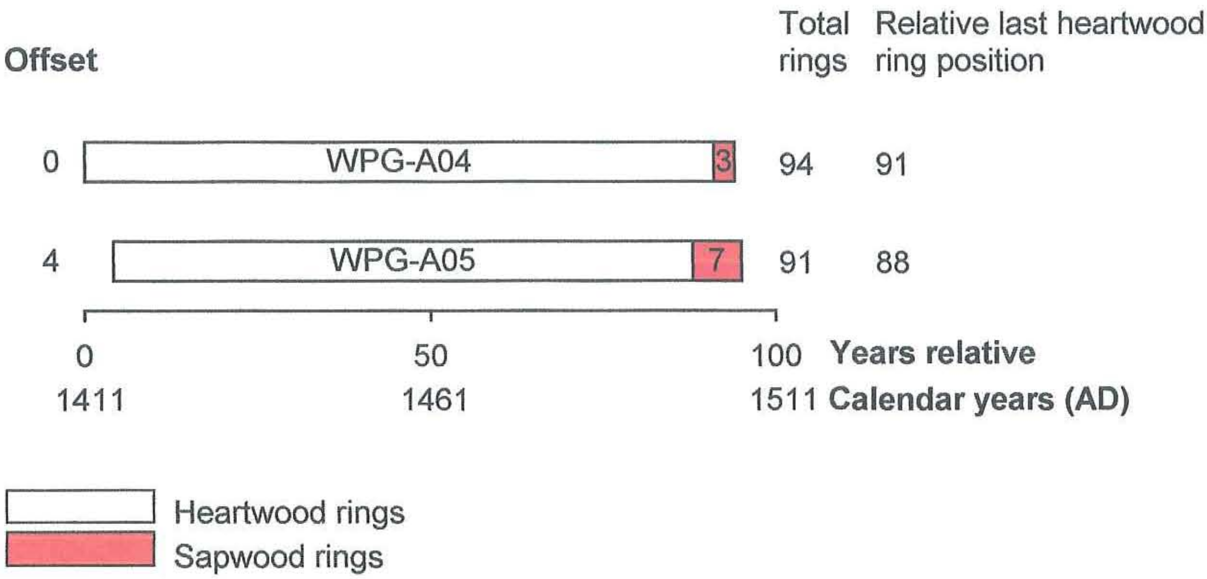
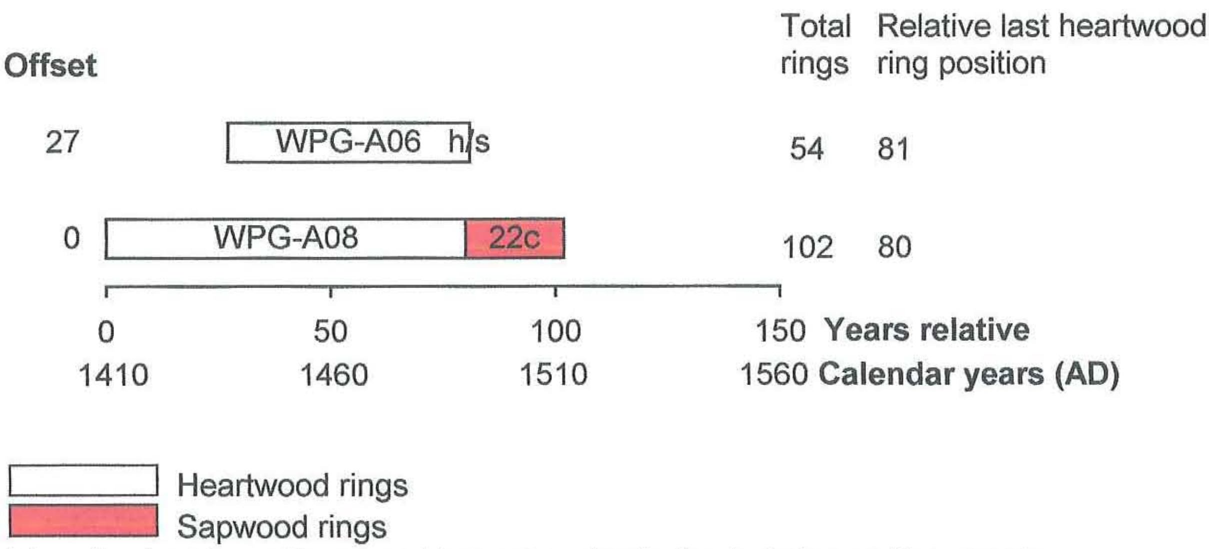


Figure 9: Bar diagram of samples in site sequence WPGASQ02



h/s = the heartwood/sapwood boundary ring is the last ring on the sample
c = complete sapwood on timber, all or part lost in sampling

Figure 10: Bar diagram of samples in site sequence WPGASQ03

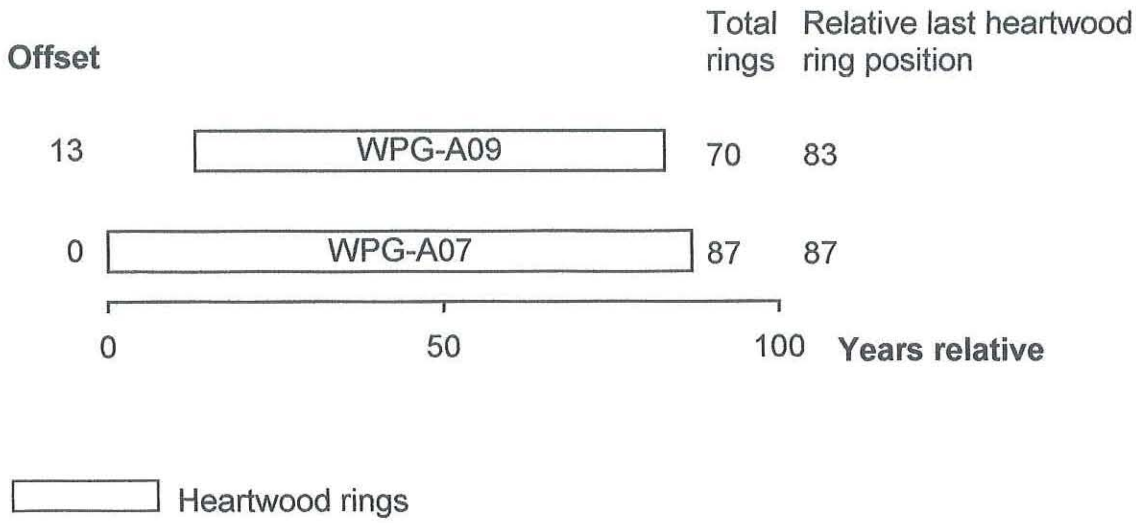
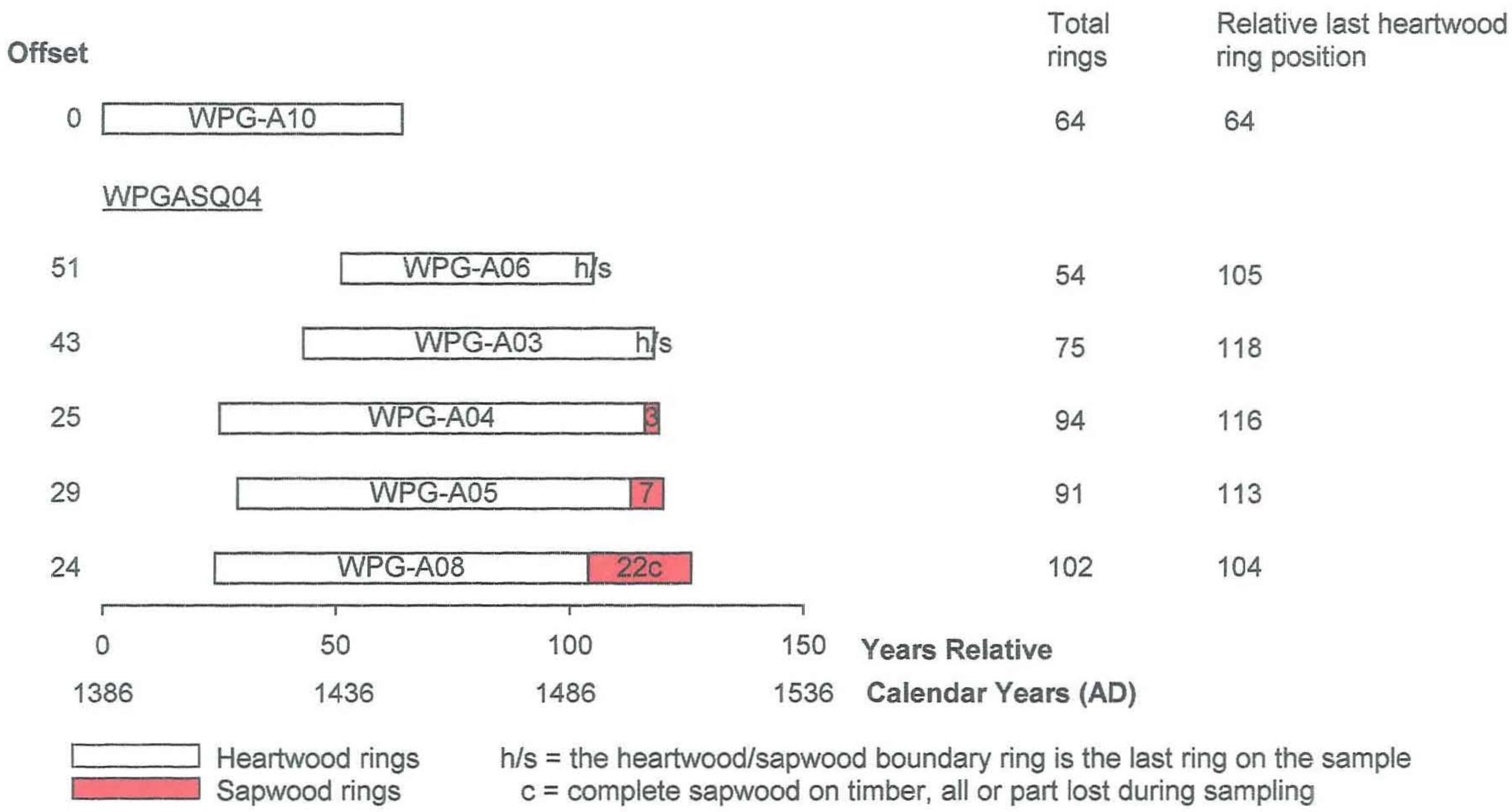


Figure 11: Bar diagram of samples in site sequence WPGASQ04 and its relative position against sample WPG-A10



Data of measured samples – measurements in 0.01mm units

WPG-A01A 80
311 100 221 251 246 179 142 180 186 170 252 238 152 299 322 296 265 324 312 386
339 274 373 459 386 304 292 411 376 392 404 401 332 372 385 261 206 196 369 374
379 116 149 142 222 156 182 212 232 253 232 311 291 216 390 260 223 233 225 193
214 200 224 238 249 170 220 266 305 207 313 242 325 213 186 318 219 284 246 182
WPG-A01B 80
231 117 208 236 263 158 164 160 151 183 215 234 168 278 321 292 245 329 307 415
357 273 354 448 374 303 304 407 376 417 395 410 330 387 382 273 210 181 371 365
348 120 138 146 196 169 174 201 243 255 239 287 305 211 368 264 220 228 243 215
230 192 235 236 240 165 212 251 307 207 305 238 324 213 190 298 216 290 238 211
WPG-A02A 122
271 261 188 194 299 250 255 314 323 254 236 184 221 258 172 171 213 169 128 144
122 143 124 192 179 127 105 119 148 177 152 137 96 91 91 95 84 88 87 66
81 88 91 67 62 56 66 72 100 105 93 86 91 109 141 129 79 99 95 83
73 81 90 105 156 219 184 146 141 120 105 107 124 133 104 107 149 105 108 80
98 87 78 102 111 83 68 90 123 92 146 141 102 76 79 80 94 73 76 108
95 88 59 72 63 60 64 66 85 75 90 79 87 66 50 60 42 47 42 56
55 47
WPG-A02B 122
279 248 181 207 287 248 242 307 302 241 309 154 227 227 186 168 202 162 127 119
108 150 137 171 165 143 107 112 163 181 117 157 96 100 96 86 91 91 82 72
80 98 98 66 60 54 62 76 101 101 95 90 91 95 159 114 80 100 93 85
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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 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 1 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 1, 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 University of 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 2 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 to 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.

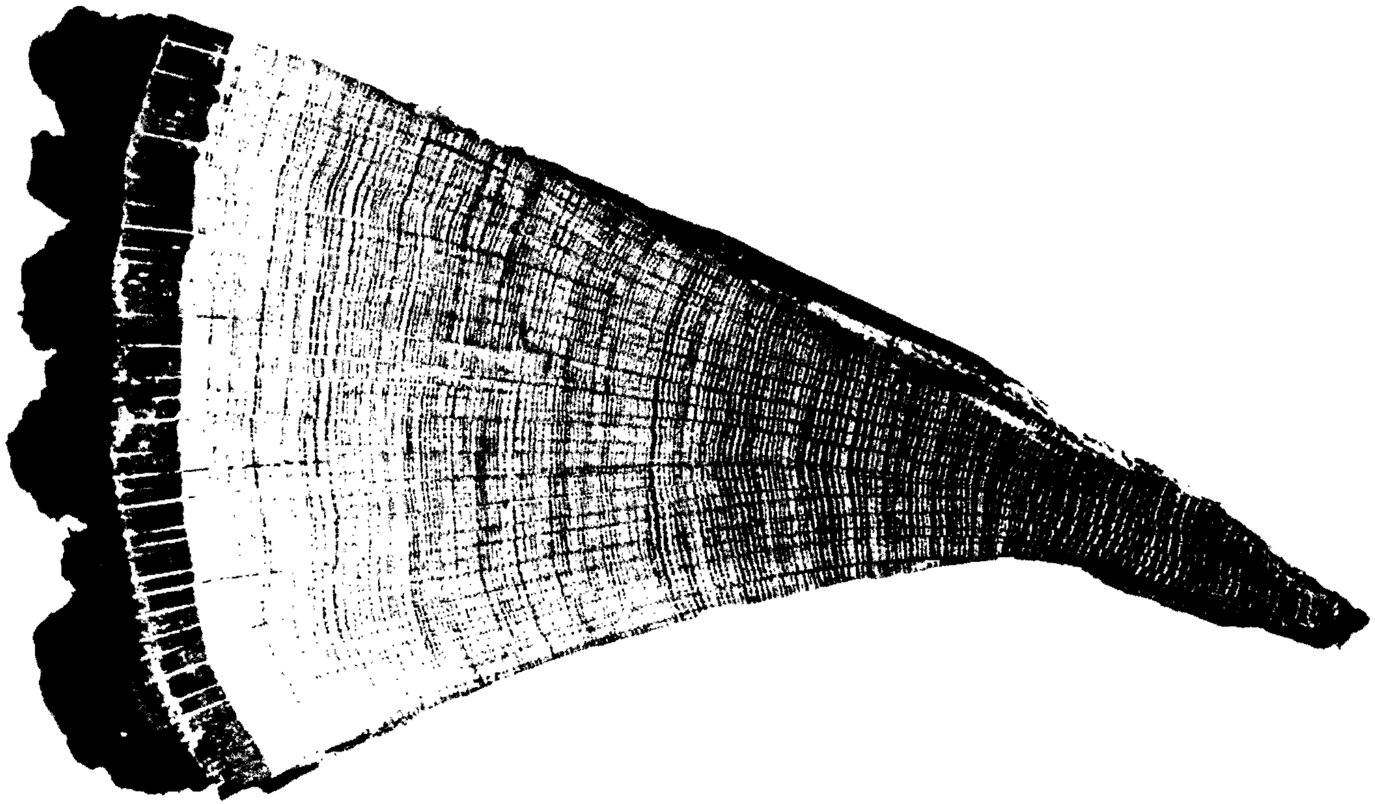


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

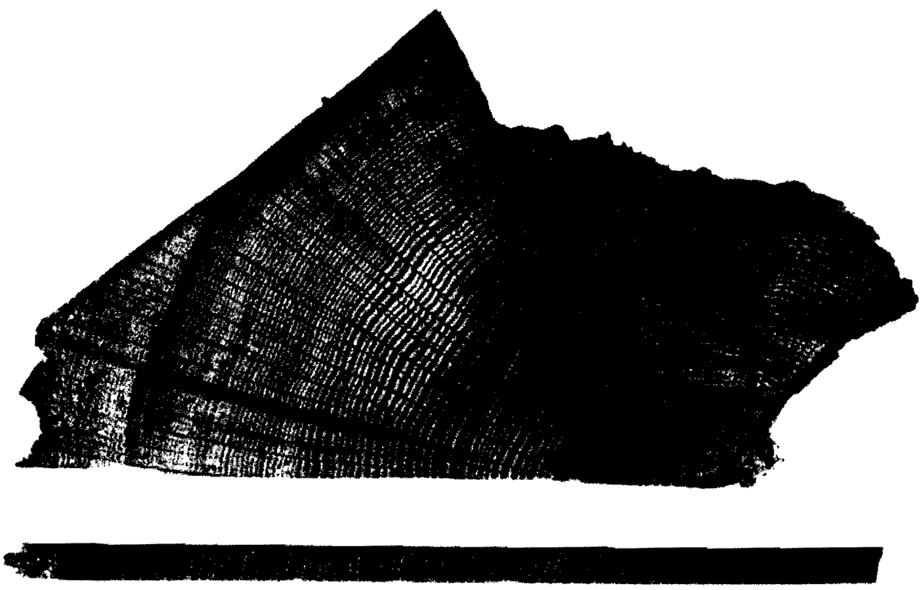


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig. 3 Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measure 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.

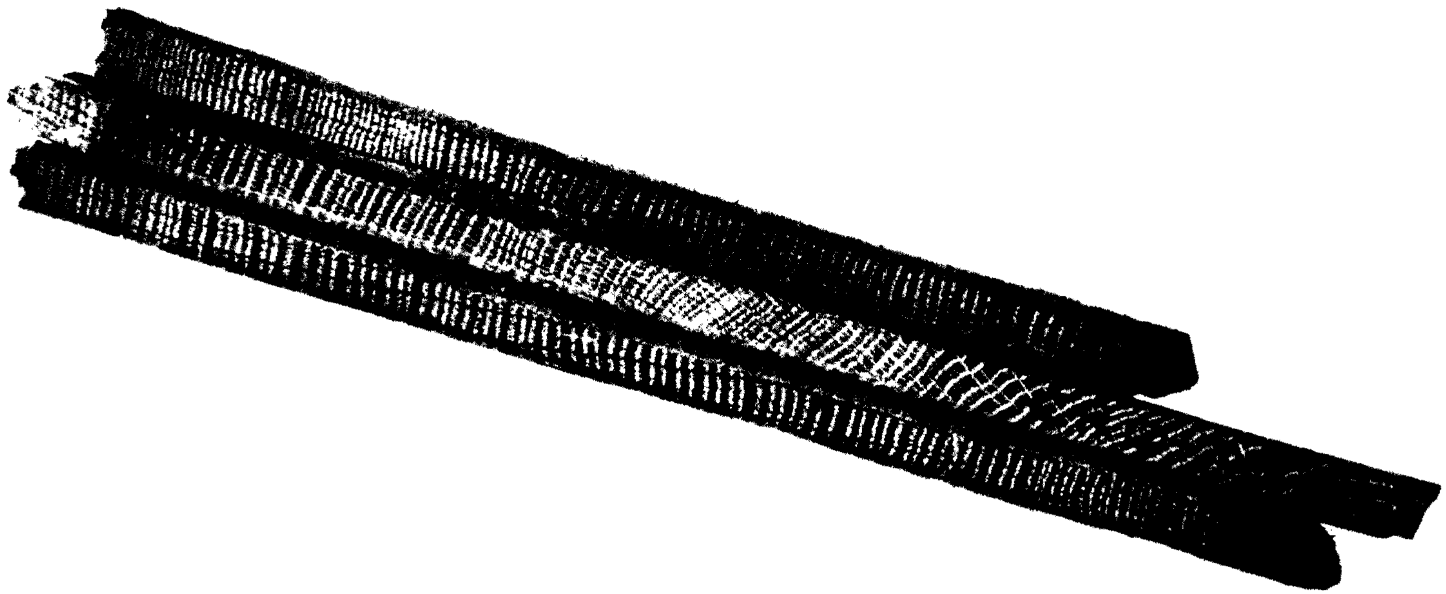


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 2; it is about 15cm long and 1cm 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.

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 2. 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 3).

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 4). 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 Fig 5 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 Fig 5. 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 5 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 straight forward 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. Actually it could be the year after if it had been felled in the first three months 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 2, 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 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 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, 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 *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

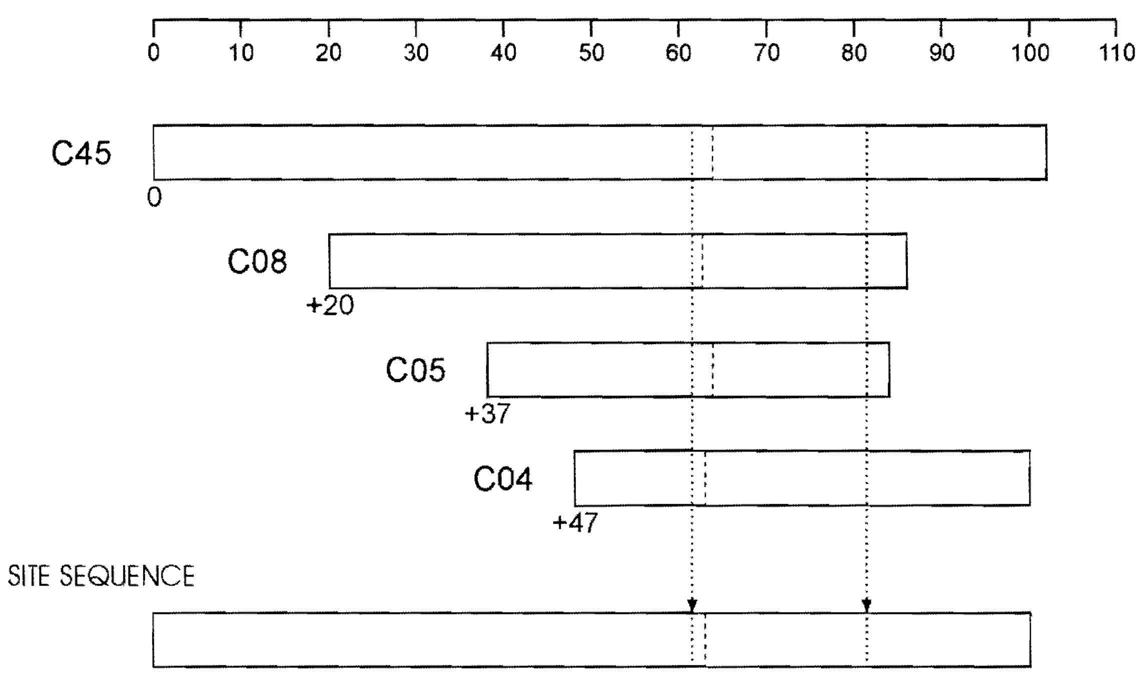


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

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 and Miles 1997, 50-55). Hence provided 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, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing 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 Fig 6 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 Fig 6. 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 Fig 7. 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 phenomena 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.

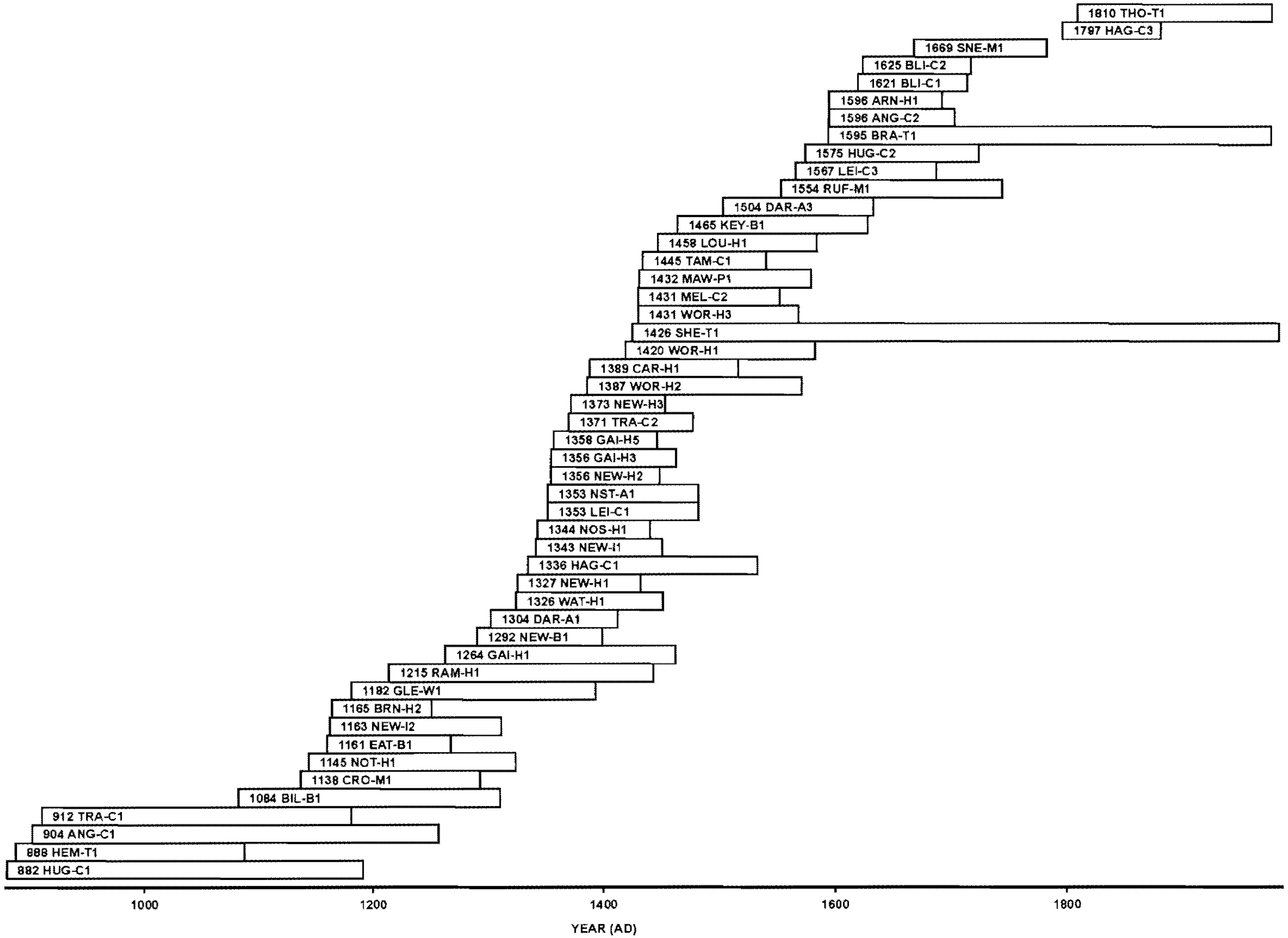
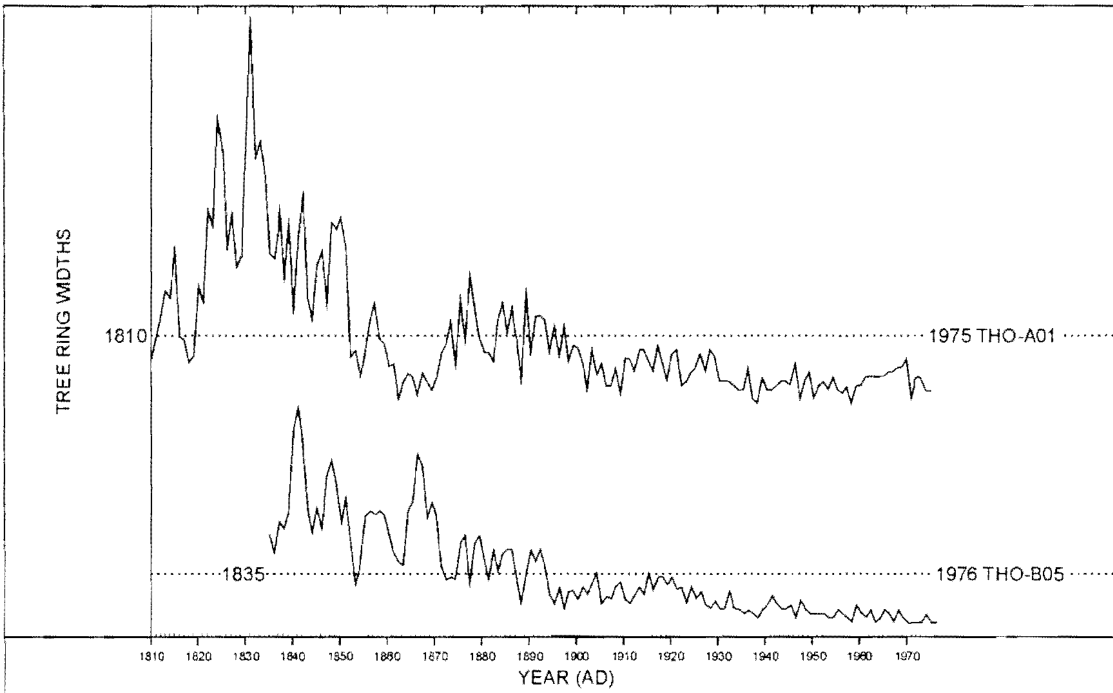


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

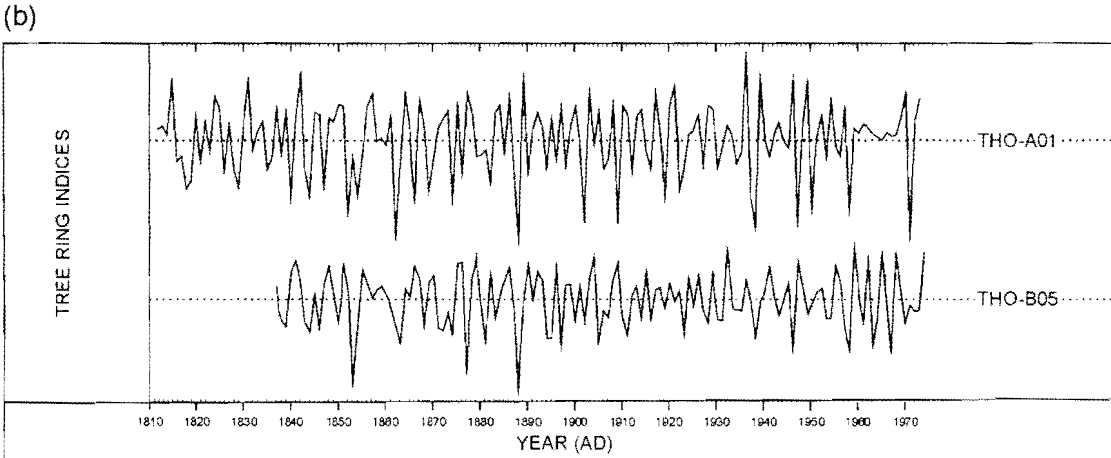


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

Fig 7. (b) The *Baillie-Pilcher* indices of the above widths. The growth-trends have been removed completely.

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