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Summary

A total of 66 samples was obtained from timbers in various areas of Ordsall Hall, of which 62 were analysed by tree-ring dating. This analysis produced six site chronologies.

The first, ORDHSQ01, comprises eight samples from original timbers of the east wing roof, of combined length 270 rings. These are dated as spanning AD 1076 - AD 1345. Interpretation of the sapwood indicates an estimated felling date in the range AD 1348 - 1373.

The second, ORDHSQ02, comprises 32 samples from the Great Hall, 'link block', and 'annex'. This has a combined length of 169 rings spanning AD 1368 - AD 1534. Interpretation of the sapwood on these samples indicates that the Great Hall was built using timber felled in AD 1512. It appears likely that the 'link block' was built at the same time.

The dating of timbers from the 'annex' shows a fireplace bressumer felled in AD 1461, almost certainly a reused piece. Two other dated timbers are unlikely to have been felled before the mid-sixteenth century and may represent the early seventeenth-century construction phase indicated on structural and stylistic grounds.

Four site chronologies, accounting for eight samples, plus another 14 ungrouped individual samples remain undated.

Keywords

Dendrochronology
Standing Building

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Introduction

Ordsall Hall, Salford (SJ 815 973; Fig 1) is an impressive and important building, substantially of heavy and close-set decorative timber framing, but with brick elements also. It stands within its own grounds on a former moated site in a recently rejuvenated urban/light industrial environment. The Hall has had a long and complex development representing several phases of building and alteration, with some demolition having taken place too. It is thus an agglomeration of structures from different periods.

The earliest remaining part of the building (see plan Fig 2), is two bays of a once much longer east wing, the original extent of this being proved by archaeological excavation in AD1995 (Greater Manchester Archaeological Contracts 1995). It is believed, on the basis of documentary evidence, that this east wing was built by Sir John Radcliffe (AD 1300 - 62) who acquired the site, consisting of a messuage, or existing building (nothing of which now remains), about 120 acres of land, plus woods and meadows, in AD 1354. In AD 1360 Sir John obtained a licence from the Bishop of Lichfield to have 'divine service solomised by a fit priest within an Oratory or Chapel at Ordsall for a period of two years'.

It is probable that this oratory was within the newly built east wing, which is described in an inquisition post mortem, upon the death of Sir John's son, Richard Radcliffe in AD 1380, as containing a hall, five chambers, a kitchen, and chapel. Dendrochronological analysis of the remains of the east wing, undertaken by the Nottingham Laboratory in AD 1993, provide an estimated felling date in the range AD 1363 - 83 for the roof timbers (Howard *et al* 1994a). The east wing appears to have existed to at least AD 1750, when it appears in a drawing of the site, but was largely gone, the result of abandonment, neglect, and decay, by AD 1812, when it is absent from a survey of that date.

It is possible that the original messuage which Sir John obtained in AD 1354 was on the site of the present Great Hall, such an interpretation being based on traces of foundation walls, found during archaeological investigation, which do not relate to any present structure. It is thought that the original building here would have centred on an open hall of cruck construction, similar to that visible at Samlesbury Hall, near Blackburn, which was built in the early-fourteenth century. There is, however, no evidence for such an interpretation. The original hall appears to have been demolished and replaced by a much grander Great Hall in AD 1512, this date again being determined by tree-ring analysis undertaken in AD 1993. This new Hall would have been built by Sir William Radcliffe. His carpenters created a framework of small square panels which were filled with cusped braces creating ornamental quatrefoils which are the distinctive feature of the surviving north front (frontispiece).

At some time in the early-seventeenth century a three-story timber-framed wing was added to the south-east of the east wing. Little timber work now remains in this 'annex', as it has been replaced by later brick-work. According to documentary sources a brick built west wing was added to the west end of the early sixteenth-century Great Hall in AD 1639. It is uncertain whether the Great Hall and the new west wing were directly connected by the west (service) cross wing of the Great Hall, hereafter called the 'link block', or whether there initially existed a gap between the two parts. In the mid-eighteenth century a final phase of building took place when an 'infill' block was added to the north of the 'annex'.

From the mid-eighteenth century a period of neglect ensued, with parts of the building, particularly the east wing, falling into disrepair. It was not until the later nineteenth century that programmes of repair and restoration were undertaken. During this time substantial portions of original timber and early brick work were removed and replaced, in a generally sympathetic style, with fresh material.

Initial sampling, AD 1993

As is intimated above, sampling and analysis by tree-ring dating of timbers of Ordsall Hall has been undertaken previously, this having been commissioned by Salford City Museums and Art Galleries in AD 1993. This initial programme of analysis, during which a total of 40 core samples was obtained, related to three areas of the site in particular. The first was the timbers of the original roof of the east wing, abutting the east end of the Great Hall. Only two trusses of this roof remain in which crown posts rise from the cambered tiebeams to a collar purlin, with braces from tiebeams to crown posts, and from crown posts to the collars. There are also braces from each crown post to the collar purlin. An illustration of a roof truss is given in Figures 3. From these roof timbers a total of 10 core samples were obtained, each sample being given the code ORD-A (for Ordsall site 'A'), and numbered 1 - 10.

The second area of sampling in the initial programme was the Great Hall. Portions of this roof, consisting of cambered tiebeams, collars, and heavy principal rafters, were accessible from the attic space of the east wing. Other, lower, timbers were available elsewhere in the Hall. An illustration of a typical truss here is given in Figure 4. A total of 22 core samples were obtained from this area, these being designated ORD-B, and numbered 11 - 32.

The third and final area at the time of initial sampling was the timbers of the southern end of the west wing. In this area are to be found main wall posts, tiebeams, and principal rafters. From these timbers a total of eight core samples were obtained, these being coded ORD-C, and numbered 33 - 40.

Second sampling, AD 2004

A second programme of sampling and analysis was undertaken in AD 2004, this being commissioned by English Heritage. This more recent work was requested to inform conservation, and a programme of repair. The English Heritage brief called for the sampling of timbers from two further areas in particular, (the areas of original sampling, the Great Hall, and the east and west wings, being excluded) with the results of both programmes of analysis being combined in a single report.

The first area was the 'annex'. The roof of this area contained a small number of timbers, almost completely hidden by a chimney stack, and only partially accessible beneath the present covering. The few available timbers comprise what appear to be a tiebeam, a wall post, brace, and a single stud post. All other roof timbers in this area appeared to be relatively modern, probably nineteenth-century, softwood replacements. These four available oak timbers were sampled, the cores being designated ORD-D, and numbered 41 - 44. It is uncertain if these four timbers are part of the Great Hall construction phase or are part of the 'annex' building phase.

The first-floor of the 'annex' contains a series of timbers set round a fireplace; two large stud-posts, a horizontal fireplace bressummer, a corner post and part of a brace. Only the three of these appeared to be suitable for tree-ring analysis, the other timbers clearly derived from very fast grown trees. There were no other suitable timbers available in this area. The three suitable oak timbers were sampled as cores ORD-D45 – 47.

The second area of sampling in this AD 2004 sampling was the 'link block' connecting the Great Hall and the west wing. The relationship between these two was slightly ambiguous, it being uncertain whether the 'link block' was part of the Great Hall construction phase, part of the west wing construction phase, or of an entirely different phase, having been constructed later to join the Great Hall and wing together.

The timbers in this area consist mainly of principal wall posts, rails, and window sills and heads, all forming the north wall of the 'link block'. Structurally these timbers appear to be contiguous with the north wall of the Great Hall, particularly at ground-floor level, although at first-floor level there are two principal posts set close together, one appearing to belong to the Great Hall, the other to the 'link block'.

Also to be found here is a main bridging beam, spanning the north-south width of the 'link block' in the ground-floor ceiling, and a mid-rail where the 'link block' and the west wing meet. The ground-floor ceiling is spanned by smaller close-set common joists. It is clear that some of the timbers in this area are more recent than others, these being very squarely cut and having machined circular saw marks on them. Other timbers, particularly the common joists, may also be of different dates, some again being more squarely cut, but not having circular saw marks on them. It is believed that this is a part of the building that saw substantial nineteenth century repairs, and many of these timbers might belong to this period. A total of 19 core samples was obtained from this area, these again being designated ORD-D, and numbered 48 – 66.

Plans showing the approximate positions of all 66 cores obtained in both programmes of sampling are given in Figures 5a - 7. Details of the samples are given in Table 1. In this report the timbers have been numbered from east to west, and described on a north - south basis as appropriate.

The Laboratory would like to take this opportunity to thank Mr Anthony Blacklay of Blacklay Associates, Architects, for his invaluable help in interpreting this site, and for his help during sampling. We would also like to thank him for the use of his plans and drawings. The Laboratory would also like to thank staff members at Ordsall Hall who were most helpful, cooperative, and generous during sampling.

Analysis

Each of the 66 samples obtained was prepared by sanding and polishing. It was seen at this point that 4 cores, ORD-C34, C40, D47, and D58, had too few rings, that is less than 54, for satisfactory analysis and these were rejected. The annual growth-ring widths of the remaining 62 samples were measured, the data of these being given at the end of the report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see appendix) and, at a minimum *t*-value of 4.5, six groups of cross-matching samples can be created.

The first group consists of eight samples, all from original timbers of the east wing roof, cross-matching with each other as shown in the bar diagram, Figure 8. The eight samples were combined at these relative positions to form site chronology ORDHSQ01 (for Ordsall Hall, site sequence '1'), with an overall combined length of 270 rings. Site chronology ORDHSQ01 was compared to a large number of relevant reference chronologies for oak, cross-matching with a series of significant *t*-values when the date of its first ring is AD 1076, and the date of its last ring is AD 1345. Evidence for this dating is given in the *t*-values of Table 2.

The second group consists of 32 samples cross-matching with each other as shown, sorted by sample location, in the bar diagram, Figure 9. As will be seen from this diagram, the group predominantly comprises samples from the Great Hall, and the 'link block', but also includes three samples from the 'annex'.

The 32 samples were combined at these relative positions to form site chronology ORDHSQ02 having an overall combined length of 169 rings. Site chronology ORDHSQ02 was also compared to a large number of relevant reference chronologies for oak cross-matching with a series of significant *t*-values when the date of its first ring is AD 1368, and the date of its last ring is AD 1534. Evidence for this dating is given in the *t*-values of Table 3.

The next four groups consist of two samples each, cross-matching with each other as shown in the bar diagrams, Figures 10 - 13. The samples of each group were combined at their indicated off-set positions to form site chronologies ORDHSQ03 - SQ06, with combined overall lengths of 126, 82, 74, and 94 rings respectively. Each of these site chronologies was compared with an extensive range of reference chronologies for oak, but there was no further satisfactory consistent cross-matching and their constituent samples must remain undated.

Each of the six site chronologies thus created was compared against the other five, and with the remaining 14 measured but ungrouped samples. There was, however, no further satisfactory cross-matching. Each of the 14 ungrouped samples was then compared individually with the reference chronologies, but again there was no further satisfactory cross-matching.

Interpretation

Analysis by dendrochronology of timbers from this site has produced six site chronologies. The first, ORDHSQ01, is made up of eight samples, all from the roof of the east wing, and is 270 rings long, these dated as spanning the period AD 1076 to AD 1345. Four of the samples in site chronology ORDHSQ01 retain the heartwood/sapwood boundary, this having an average date of AD 1332. Using a 95% confidence limit of 15 to 40 for the number of sapwood rings on mature oaks from this part of England would give the timbers represented an estimated felling date in the range AD 1348 – 73.

The second site chronology comprises 32 samples predominantly from the Great Hall and the 'link block', but including three samples from the 'annex'. This site chronology is 201 rings long, with these rings dated as spanning the years AD 1334 to AD 1534. A number of samples in this site chronology retain complete sapwood, that is, they have the last ring produced by the tree they represent before it was felled.

The earliest definite felling represented by any sample in site chronology ORDHSQ02, is AD 1461, found on sample ORD-D45, from the fireplace bressummer of the 'annex'. The next felling appears to be represented by samples from the Great Hall. Three samples from this area, ORD-B15, B16, and B24, all retain complete sapwood, and all have the same last measured ring date, this being AD 1512. A number of other samples from the Hall have lost only very small portions of sapwood, which was complete on the timber, the loss being consistent with a felling date of AD 1512 for the timbers represented by these. The relative positions of the heartwood/sapwood boundary on the other dated samples from the Great Hall are also highly consistent in representing timbers of a single phase of felling in AD 1512.

None of the samples from the 'link block' retain complete sapwood, and it is thus not possible to be so precise as to the felling date of these timbers as those of the Great Hall. However, the relative positions of the heartwood/sapwood boundaries on the samples from the two areas are virtually identical. The average last heartwood ring date of the 16 samples from the Great Hall, where it exists, is AD 1487, that on the seven samples from the 'link block', where it exists, as AD 1488. This would suggest that the felling of all the dated timbers in the two areas probably took place at about the same time.

The latest dates are found on two cores from the roof of the 'annex', samples ORD-D41 and D42, with last ring dates of AD 1521 and AD 1534 respectively.

Neither of these samples retains even the heartwood/sapwood boundary, this possibly as a consequence of the limited access to these timbers in the roof space. It is thus not possible to say when these timbers were felled except that it is unlikely to be before AD 1535 and AD 1549 respectively, these dates again being based on a 95% confidence limit of a minimum of 15 sapwood rings.

Conclusion

Analysis by dendrochronology has produced a number of chronologies from this site, only two of which can be dated, although these comprise the majority of samples obtained. As shown in the original AD 1993 analysis, the earliest extant part of the building is the remains of the east wing roof. Interpretation of the sapwood indicates that these timbers are likely to have been felled sometime between AD 1348 and AD 1373. Such a date is highly consistent with that given in the AD 1995 report which, on the basis of documentary evidence, indicates that Sir John Radcliffe obtained the site in AD 1354, and presumably began to enlarge an existing building by the addition of a new wing to the east.

It would appear that the existing hall which Sir John acquired and the new east wing he built provided sufficient suitable accommodation for the next 150 or so years. In the early-sixteenth century, however, it would appear that the early hall on the site, to which the east wing was presumably attached, was demolished, and replaced by a modern Great Hall. This was built using timber felled in AD 1512.

The section known as the 'link block' was probably built at this time too as part of the Great Hall construction phase, demonstrating that it does not relate to the west wing construction phase, or represent a still later in-fill piece. Surprisingly perhaps, given that there were suspicions about the extent of repairs in this area, there is no certain later timber found here, although several samples remain undated and these might represent nineteenth-century repairs.

The roof of the 'annex' contains the latest material of all. Two samples from this area have last measured ring dates of AD 1521 and AD 1534, but do not include even the heartwood/sapwood boundary. It is unlikely that these timbers were felled before the middle of the sixteenth century, and thus cannot be part of the Great Hall construction phase. It seems probable that these timbers represent all that remains of the construction of this part of the building which, on documentary grounds, is believed to have been built in AD 1639.

One timber from the 'annex', represented by sample ORD-D45, was, however, certainly felled in AD 1461. Given that this is a fireplace bressummer it is possible that it represents a reused beam.

Of the 62 samples obtained and measured, 22 are undated, of which 14 are ungrouped. Most of the undated samples are from timbers of the west wing. It is possible that this lack of cross-matching and dating is a result of some of a few of these samples showing some slight distortion to the growth rings, while one or two others are slightly complacent. Other individual, undated, samples also show some distortion, ORD-A01 for example, or some compaction to their growth rings, ORD-A09 for instance. It is possible too that some timbers may be later replacements, and represent singletons, such often being difficult to date individually.

Judging by the high *t*-values obtained between some samples it is likely that some timbers have been derived from the same tree. Samples ORD-A07 and A10, for example, cross-match with a value of t=12.3, and two timbers in the Great Hall may also have been derived from another, single, tree. Other *t*-values seen amongst some samples from the roof of the east wing, Great Hall, and the 'link block' would suggest that many of the trees used were growing fairly close to each other, in the same copse or stand of woodland.

Many other samples do not cross-match with each other and this might suggest the use of trees from different sources, and of different felling dates. This is particularly so with the timbers of the west wing roof, and to a certain extent, those from the 'link block'.

The results obtained here thus reinforce the benefits of applying tree-ring analysis to buildings that are thought to be accurately and reliably dated on the basis of documentary evidence and architectural features. The tree-ring analysis of the east wing concurs very closely with the documentary sources and stylistic evidence, eg the use of lap-joints throughout the roof. It also indicates very precisely the construction date of the Great Hall and importantly illustrates the date of the 'link block' about which there was some uncertainty. It shows too that parts of the 'annex' are certainly later than either the east wing or the Hall.

Unfortunately, tree-ring analysis has not been able to produce dating evidence for the west wing. It might be possible to rectify this but it would require further and more extensive sampling from this area. It might also be possible to refine the felling date of the timbers from the east wing, which was not part of this more recent programme of sampling, but this too would require further coring, particularly of timbers with sapwood. Should the opportunity to undertake such sampling arise it is strongly recommended that this be done to further elucidate the historic development of this complex building.

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Table 1: Details of samples from Ordsall Hall, Salford

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	East wing roof					
ORD-A01	East strut, truss 1	60	no h/s	------	------	------
ORD-A02	Brace, king post to purlin, truss1 - gable	200	h/s	AD 1127	AD 1326	AD 1326
ORD-A03	South strut, truss 1	194	h/s	AD 1147	AD 1336	AD 1340
ORD-A04	West principal rafter, truss 1	147	no h/s	AD 1080	------	AD 1226
ORD-A05	West common rafter 3, bay 1	93	no h/s	AD 1125	------	AD 1217
ORD-A06	East principal rafter, truss 1	167	no h/s	AD 1076	------	AD 1242
ORD-A07	Brace, king post to purlin, truss 1 -2	177	h/s	AD 1153	AD 1329	AD 1329
ORD-A08	West strut, tiebeam to king post, truss 2	242	5	AD 1104	AD 1340	AD 1345
ORD-A09	Collar, frame 7, bay 1	178	no h/s	------	------	------
ORD-A10	East strut, tiebeam to kingpost, truss 2	135	no h/s	AD 1158	------	AD 1292
	Great Hall					
ORD-B11	Rail, truss 1, south side	68	15c	AD 1444	AD 1496	AD 1511
ORD-B12	South principal rafter, truss 2	126	27C	------	------	------
ORD-B13	King post, truss 1	86	11	AD 1410	AD 1484	AD 1495
ORD-B14	Rail, truss 1, north side	73	6	------	------	------
ORD-B15	North principal rafter, truss 1	128	25C	AD 1385	AD 1487	AD 1512
ORD-B16	South principal rafter, truss 1	99	22C	AD 1414	AD 1490	AD 1512
ORD-B17	Rail, truss 2, south side	87	12	------	------	------
ORD-B18	North principal rafter, truss 2	77	h/s	AD 1412	AD 1488	AD 1488
ORD-B19	King post, truss 2	80	17	AD 1423	AD 1485	AD 1502
ORD-B20	Collar, truss 2	85	12	------	------	------

Table 1: continued

Sample Number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Great Hall continued					
ORD-B21	Rail, truss 2, north side	85	32C	------	------	------
ORD-B22	Rail, truss 2, south side	66	h/s	AD 1417	AD 1482	AD 1482
ORD-B23	Rail, truss 2, north side	60	18	AD 1427	AD 1468	AD 1486
ORD-B24	South principal rafter, truss 5	92	30C	AD 1421	AD 1482	AD 1512
ORD-B25	Collar, truss 6	60	h/s	AD 1423	AD 1482	AD 1482
ORD-B26	North principal rafter, truss 7	86	h/s	AD 1399	AD 1484	AD 1484
ORD-B27	Tiebeam, truss 8	82	10	------	------	------
ORD-B28	Door head, truss 9	89	14c	AD 1421	AD 1495	AD 1509
ORD-B29	Door jamb, truss 9	77	20c	AD 1435	AD 1491	AD 1511
ORD-B30	Rail, truss 9	82	12c	AD 1429	AD 1498	AD 1510
ORD-B31	Rail, truss 9	89	12	AD 1417	AD 1493	AD 1505
ORD-B32	Main post 2, truss 9	74	h/s	AD 1421	AD 1494	AD 1494
	West wing roof					
ORD-C33	East principal rafter, truss 2	60	h/s	------	------	------
ORD-C34	East brace, rafter to upper purlin, truss 1 - 2	nm	---	------	------	------
ORD-C35	West brace, rafter to upper purlin, truss 1 - 2	69	h/s	------	------	------
ORD-C36	West brace, rafter to upper purlin, truss 2 - 3	61	15	------	------	------
ORD-C37	West upper purlin, truss 2 - 3	59	h/s	------	------	------
ORD-C38	Tiebeam, truss 4	73	8	------	------	------
ORD-C39	East brace, rafter to upper purlin, truss 4 - 5	74	h/s	------	------	------
ORD-C40	West brace, rafter to upper purlin, truss 4 - 5	nm	---	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	'Annex' roof					
ORD-D41	Corner post	69	no h/s	AD 1453	------	AD 1521
ORD-D42	Collar	110	no h/s	AD 1425	------	AD 1534
ORD-D43	Stud post	60	no h/s	------	------	------
ORD-D44	Brace	59	no h/s	------	------	------
	'Annex' fireplace timbers					
ORD-D45	Fireplace bressummer beam	67	17C	AD 1395	AD 1444	AD 1461
ORD-D46	Outer stud post	62	h/s	------	------	------
ORD-D47	Corner wall post	nm	---	------	------	------
	'Link block' – ground floor					
ORD-D48	Main central stud post	126	4	AD 1369	AD 1490	AD 1494
ORD-D49	Corner post / hanging stile	66	h/s	AD 1413	AD 1478	AD 1478
ORD-D50	South cross-rail	70	no h/s	AD 1382	------	AD 1451
ORD-D51	South mid rail	79	no h/s	AD 1395	------	AD 1473
ORD-D52	Central bridging beam	54	no h/s	AD 1402	------	AD 1455

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	'Link block' – first floor					
ORD-D53	East wall post / corner post	97	h/s	AD 1386	AD 1482	AD 1482
ORD-D54	Window sill	73	no h/s	AD 1366	------	AD 1438
ORD-D55	North window jamb	57	4	AD 1444	AD 1496	AD 1500
ORD-D56	South window jamb	73	h/s	AD 1412	AD 1484	AD 1484
ORD-D57	Brace to cross beam or wall plate	55	no h/s	AD 1368	------	AD 1422
ORD-D58	Top wall plate	nm	---	------	------	------
ORD-D59	South corner post	54	no h/s	AD 1366	------	AD 1419
ORD-D60	Window head / wall plate	59	no h/s	------	------	------
	Ground floor, ceiling joists					
ORD-D61	North joist number 9	71	no h/s	------	------	------
ORD-D62	North joist number 13	84	no h/s	------	------	------
ORD-D63	South joist number 3	54	h/s	AD 1442	AD 1495	AD 1495
ORD-D64	South joist number 4	54	h/s	AD 1440	AD 1493	AD 1493
ORD-D65	South joist number 6	56	no h/s	------	------	------
ORD-D66	South joist number 8	54	no h/s	------	------	------

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

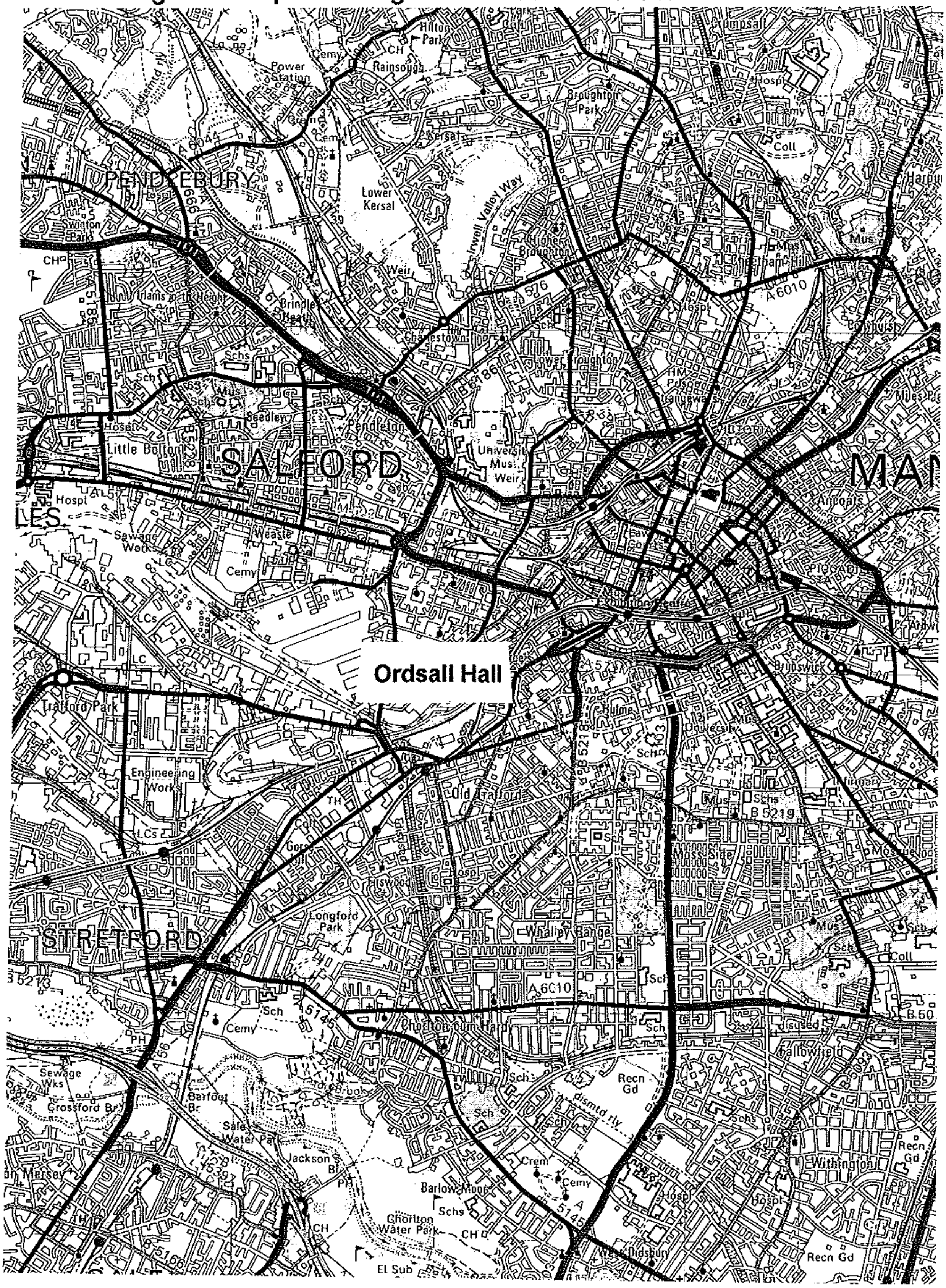
Table 2: Results of the cross-matching of site chronology ORDHSQ01 and relevant reference chronologies when first ring date is AD 1076 and last ring date is AD 1345

Reference chronology	Span of chronology	*t*-value	
England	AD 401 – 1981	7.9	(Baillie and Pilcher 1982 unpubl)
East range, Carlisle Guildhall, Cumbria	AD 976 – 1382	7.2	(Howard *et al* 1994b)
Brecon Cathedral, Powys	AD 996 – 1227	7.1	(Howard *et al* 1994a)
Carlisle Castle, Cumbria	AD 968 – 1446	6.9	(Arnold *et al* 2004)
Scotland	AD 946 – 1975	6.6	(Baillie 1977)
Horniglow Street, Burton upon Trent, Staffs	AD 1101 – 1345	6.1	(Howard *et al* 1995)
Manor House, Abbey Green, Burton upon Trent, Staffs	AD 1162 – 1339	5.9	(Howard *et al* 1998 unpubl)
East Midlands	AD 882 – 1981	5.3	(Laxton and Litton 1988)

Table 3: Results of the cross-matching of site chronology ORDHSQ02 and relevant reference chronologies when first ring date is AD 1368 and last ring date is AD 1534

Reference chronology	Span of chronology	*t*-value	
The Gables, Little Carlton, Notts	AD 1389 – 1516	8.6	(Howard *et al* 1986)
Offerton Hall, Offerton, Derbys	AD 1401 – 1592	8.3	(Howard *et al* 1995)
Wetton Church, Staffs	AD 1368 – 1630	7.7	(Arnold *et al* 2003)
England	AD 401 – 1981	7.6	(Baillie and Pilcher 1982 unpubl)
Combermere Abbey	AD 1363 – 1564	7.6	(Howard *et al* 2003)
Staircase House, Stockport, Greater Manchester	AD 1489 – 1656	7.6	(Howard *et al* 2003)
East Midlands	AD 882 – 1981	7.0	(Laxton and Litton 1988)
MC10---H	AD 1386 – 1585	6.5	(Fletcher 1978 unpubl)

Figure 1: Map to show general location of Ordsall Hall



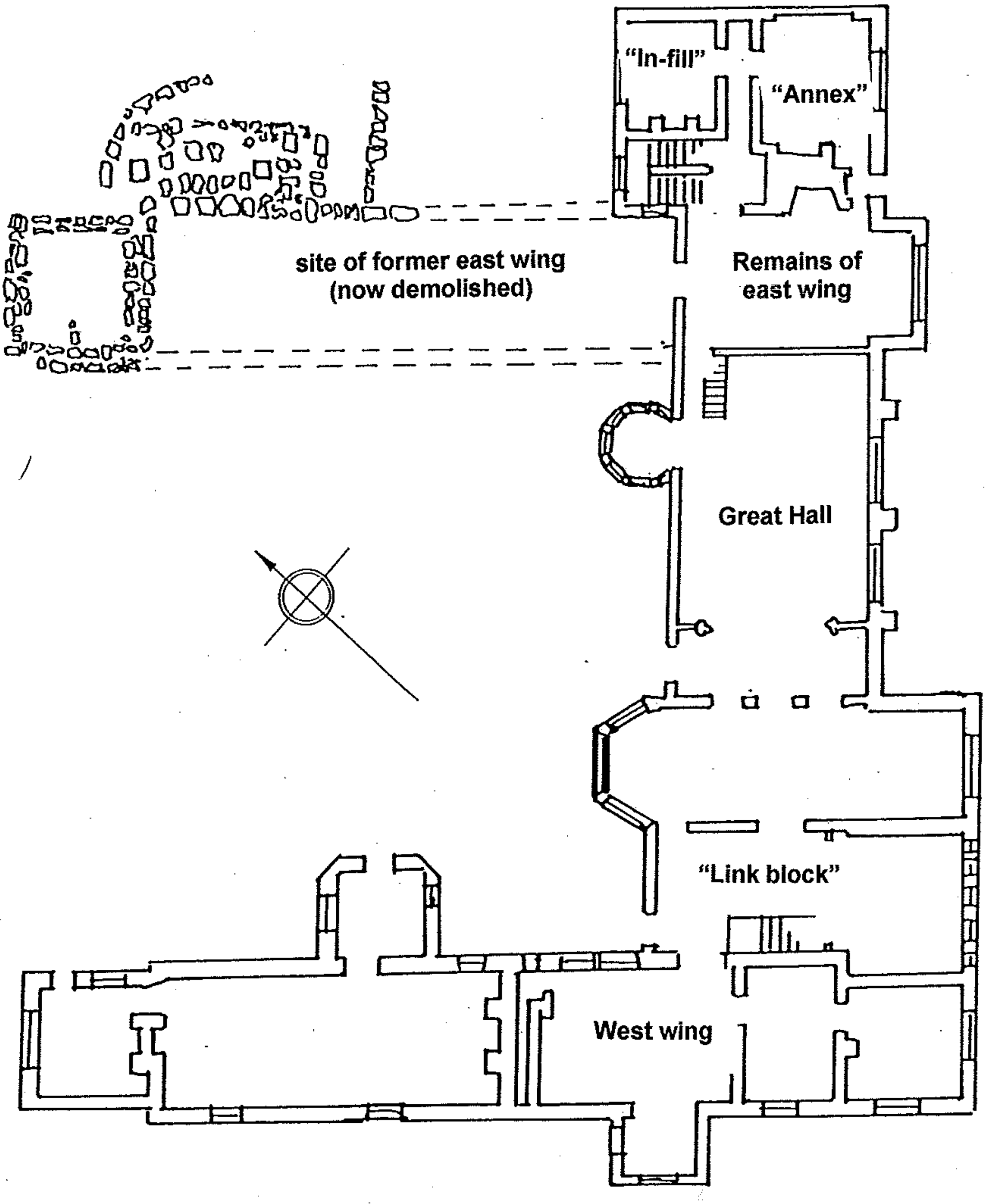


Figure 2: General plan of Ordsall Hall

Figure 3: Illustration of truss from the roof of the east wing

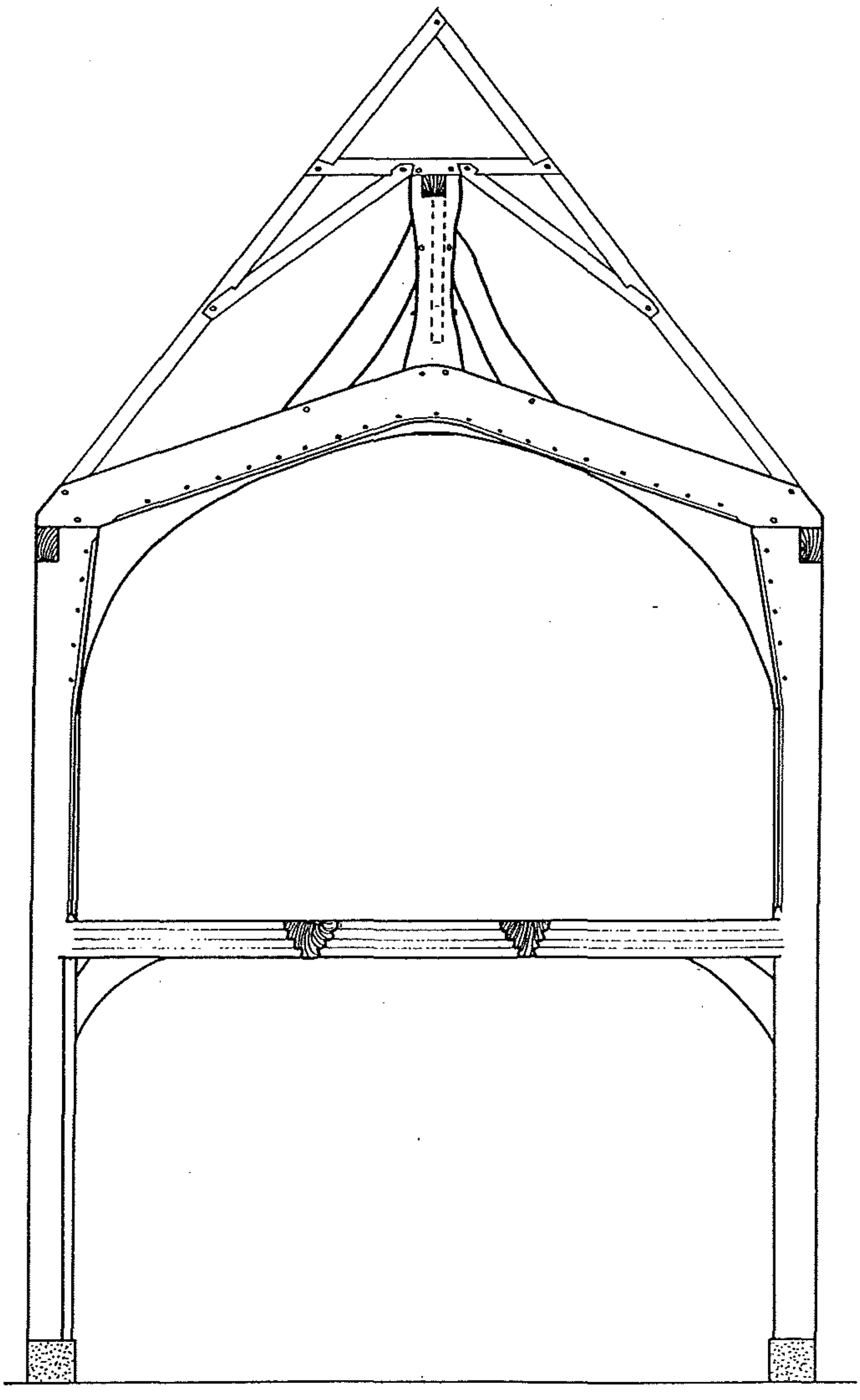


Figure 4: Illustration of truss from the Great Hall

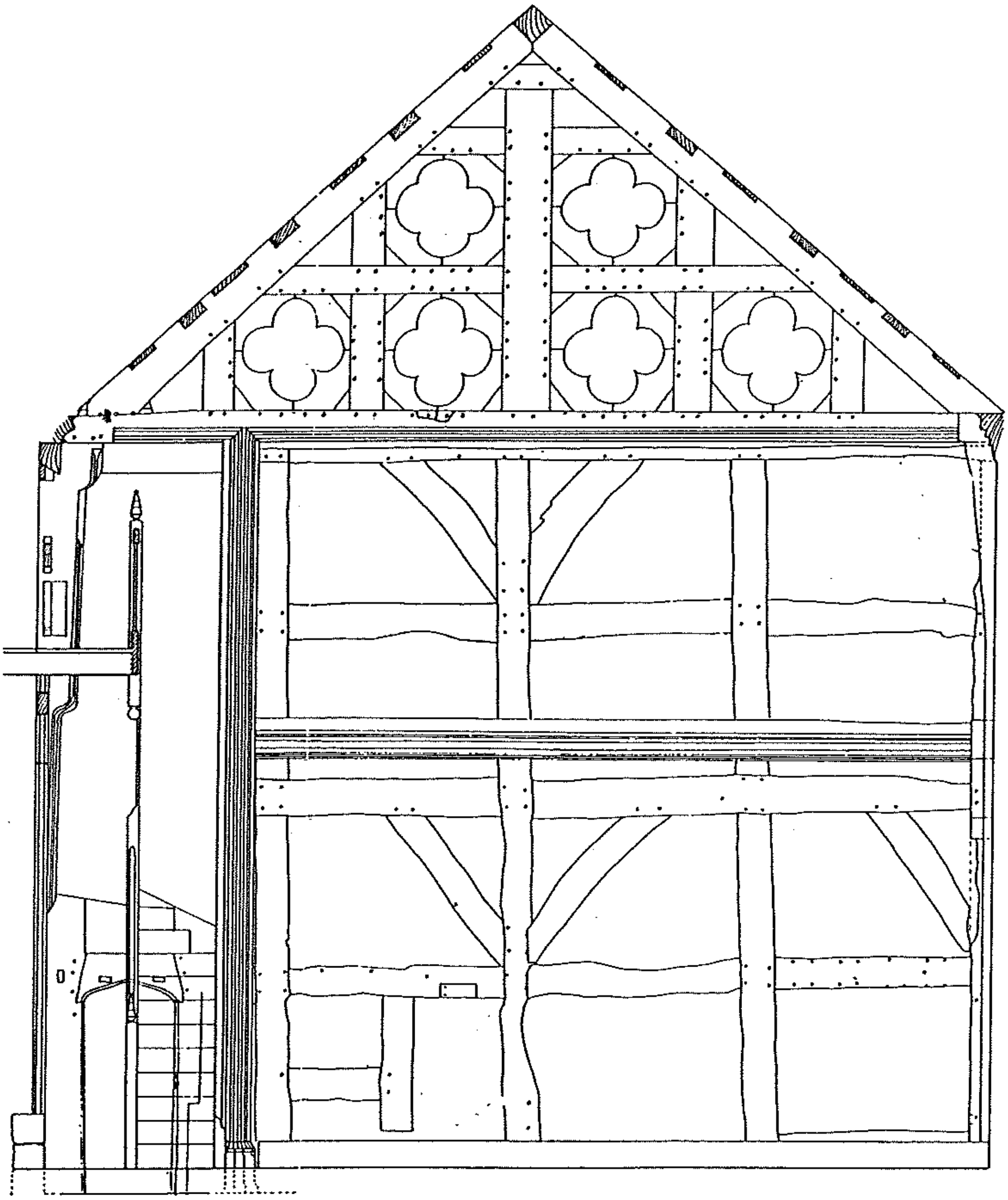


Figure 5a: Drawing to show approximate position of sampled timbers in the roof of the east wing (viewed from the north looking south)

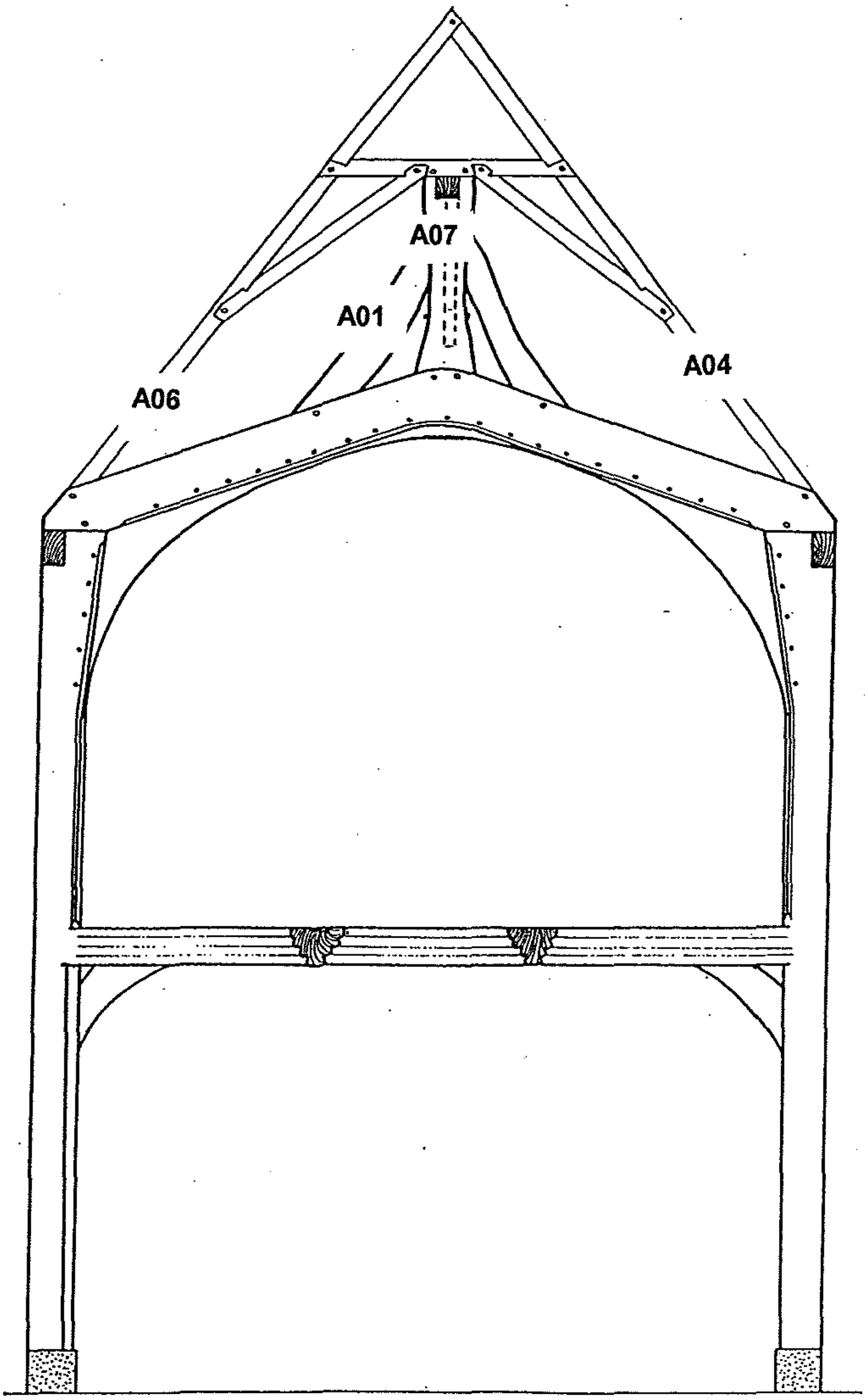


Figure 5b: Drawing to show approximate position of sampled timbers in the roof of the east wing (viewed from the north looking south)

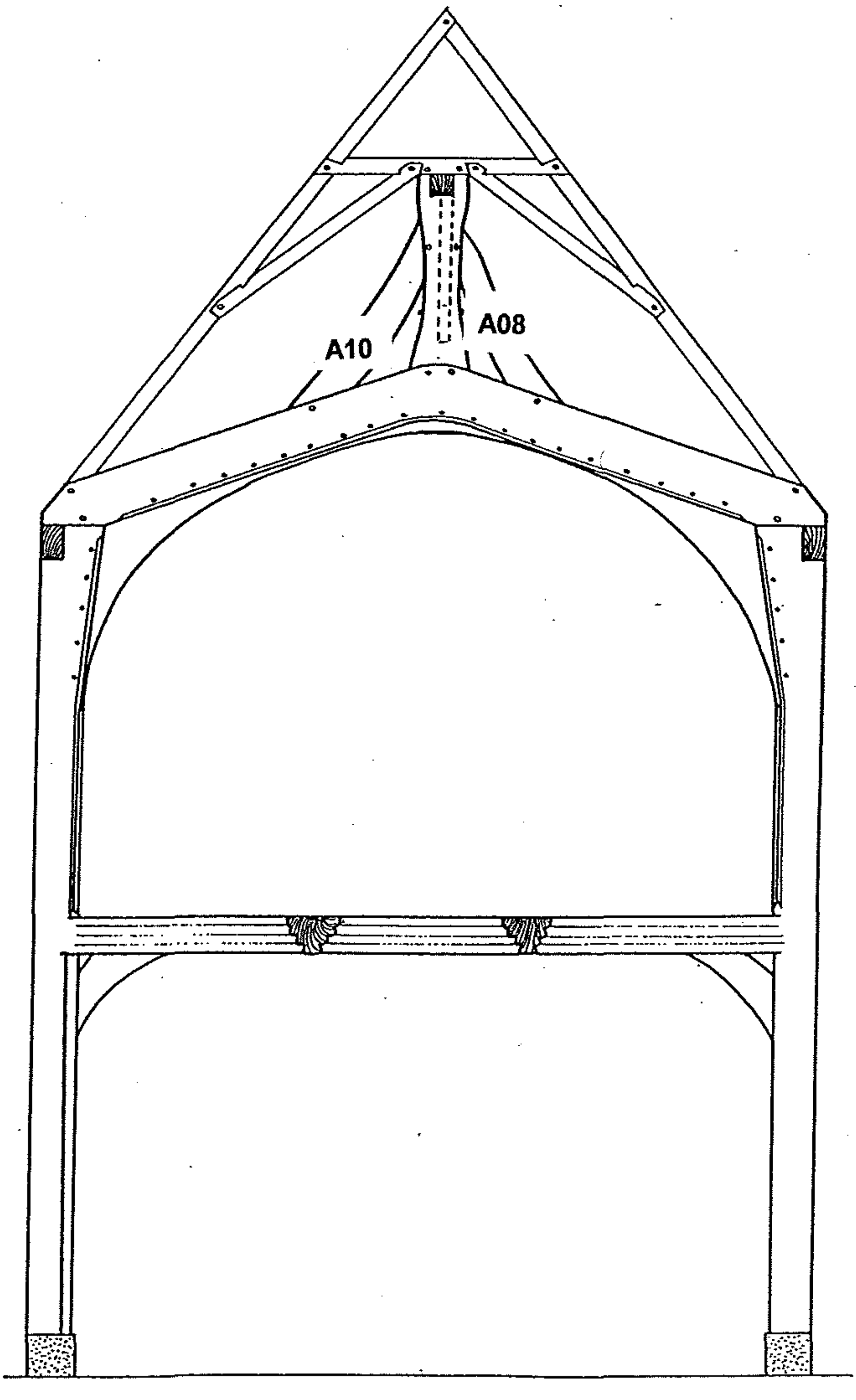


Figure 5c: Drawing to show approximate position of sampled timbers in the roof of the east wing (viewed from the east looking west)

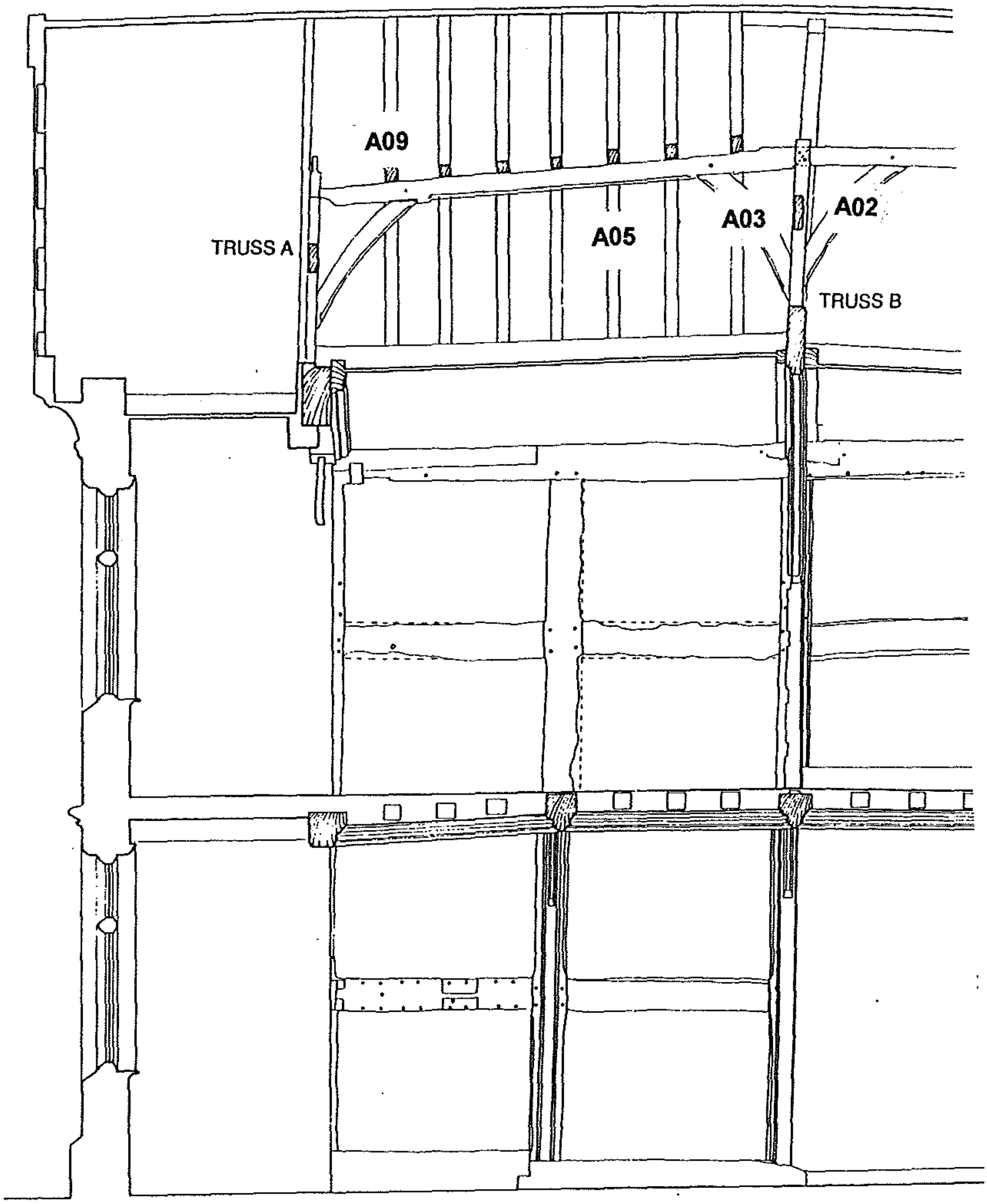


Figure 6a: Drawing to show approximate position of sampled timbers from the Great Hall and the "link block" (based on ground-floor plan)

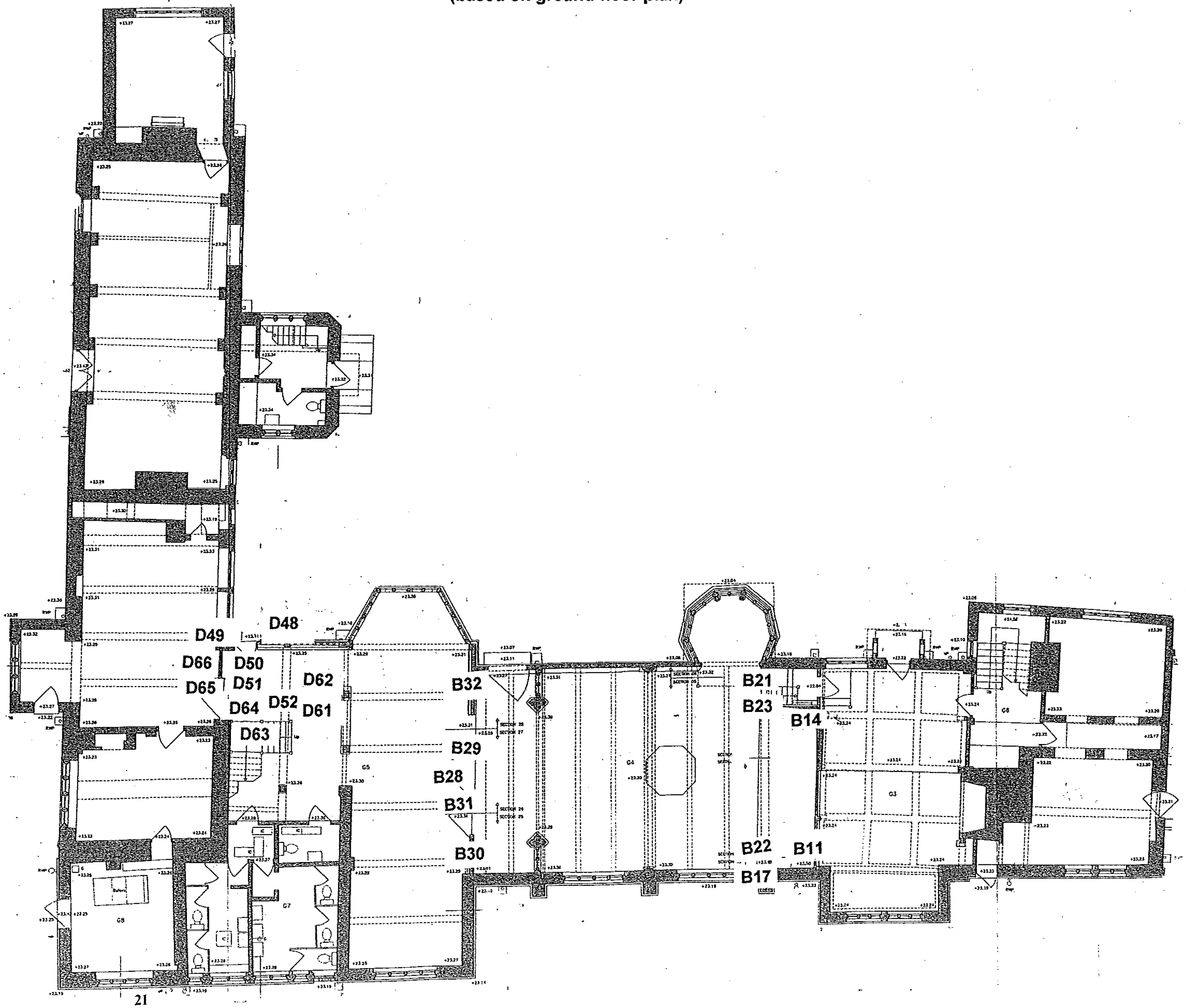


Figure 6b: Drawing to show approximate position of sampled timbers from the Great Hall, the west wing, and the "link block" (based on first-floor plan)

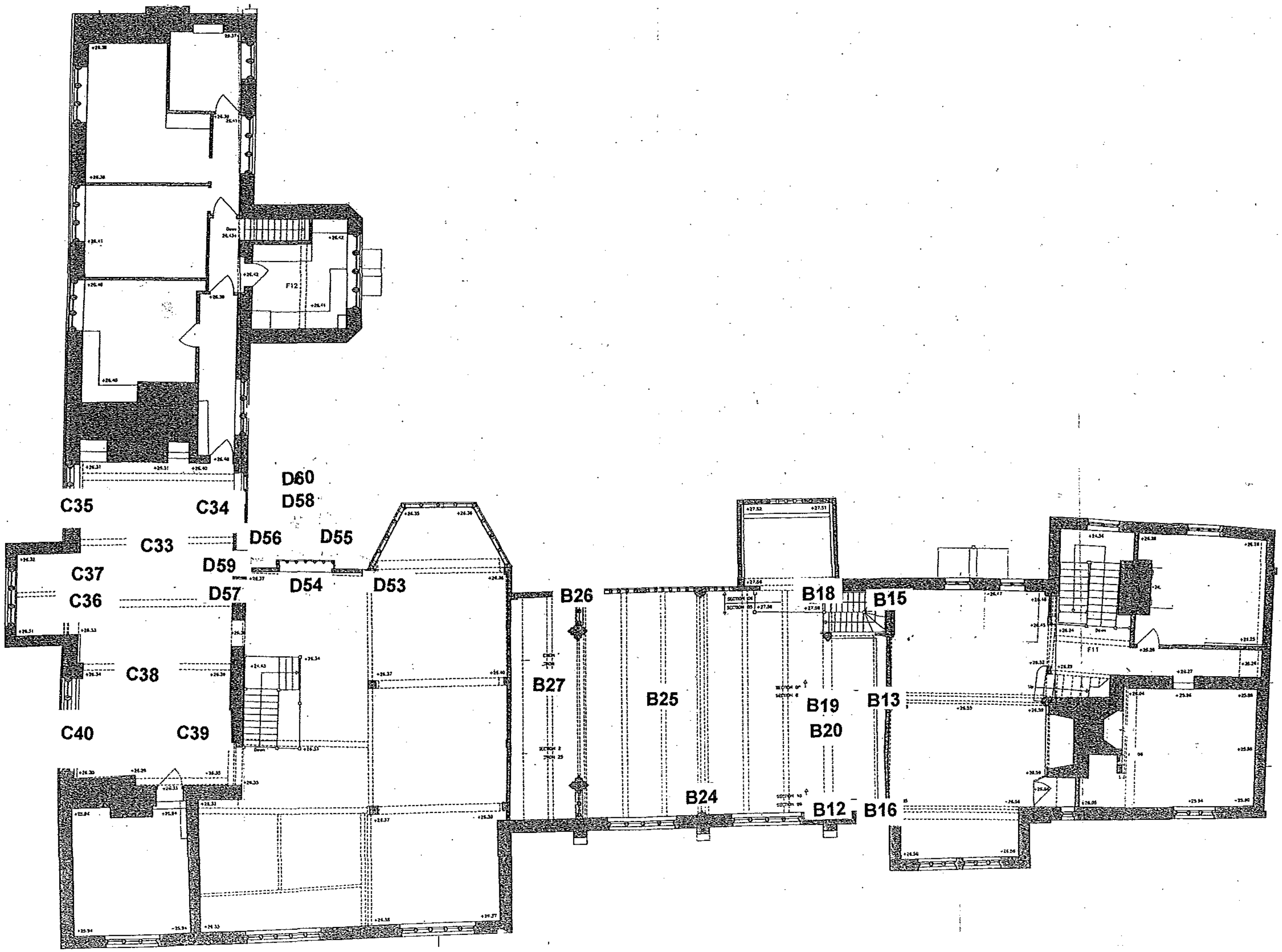


Figure 7: Drawing to show approximate position of sampled timbers from the "annex" (viewed from the east looking west)

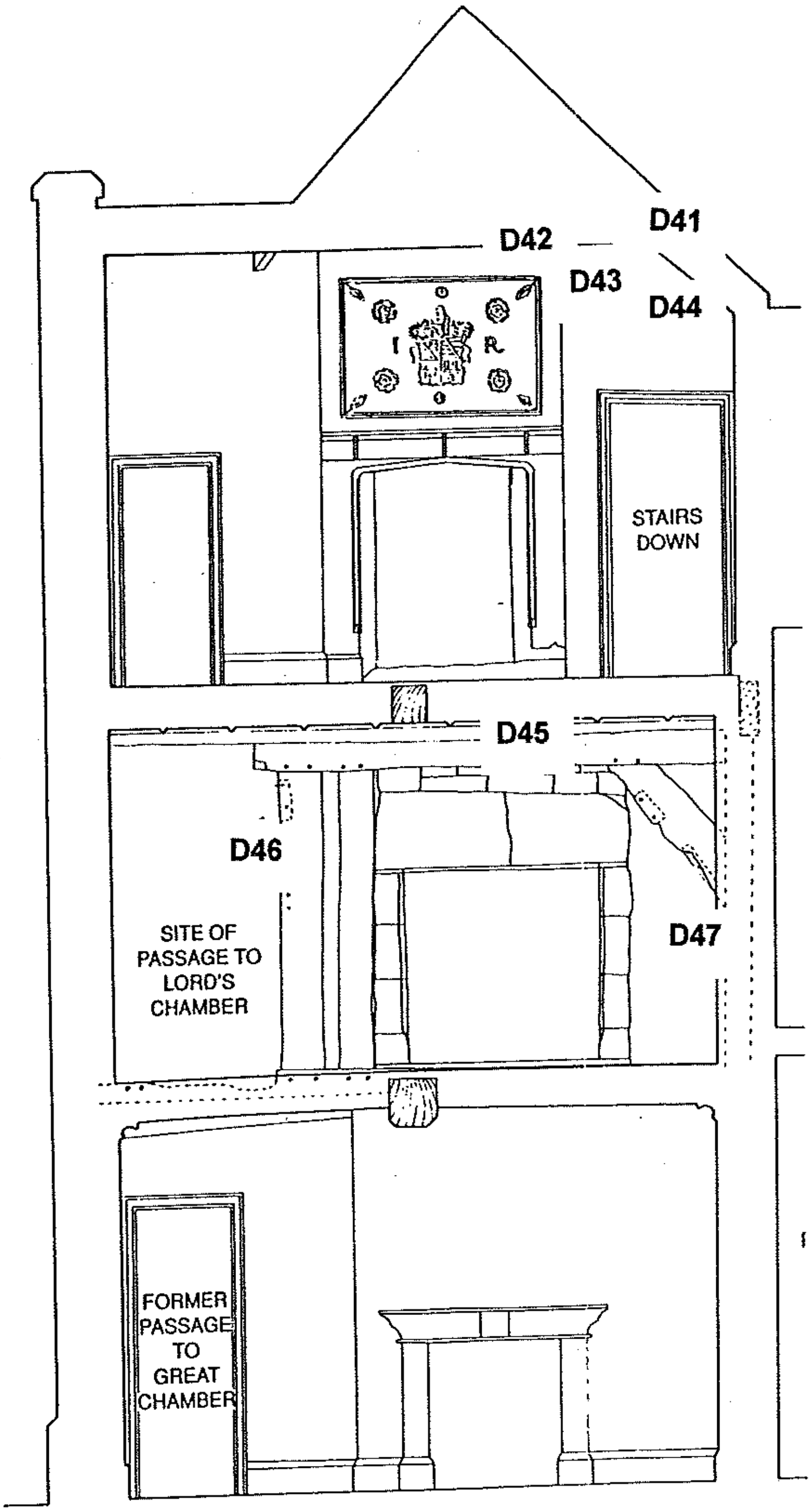
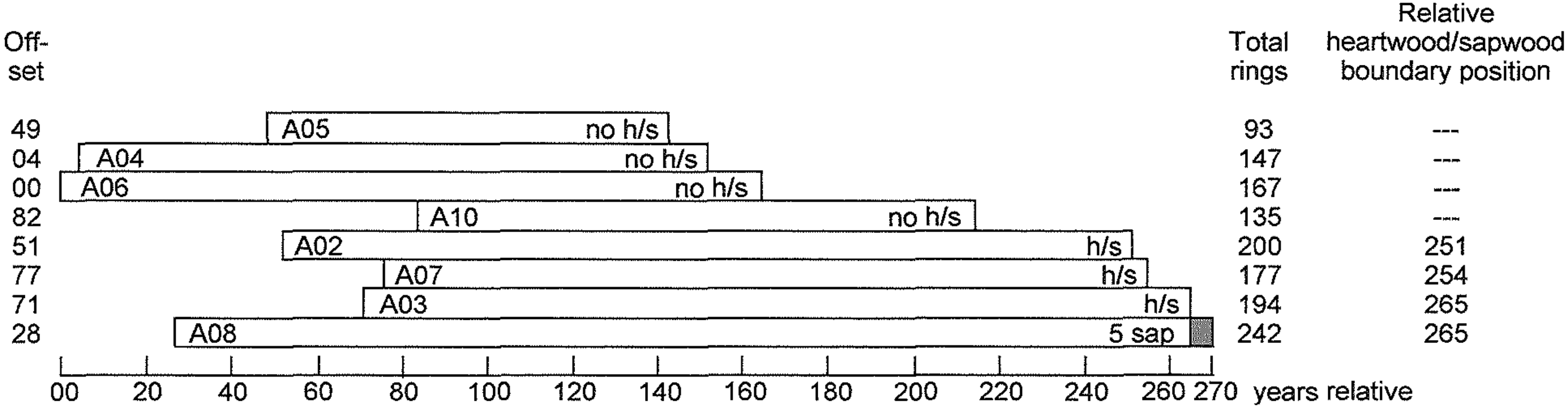
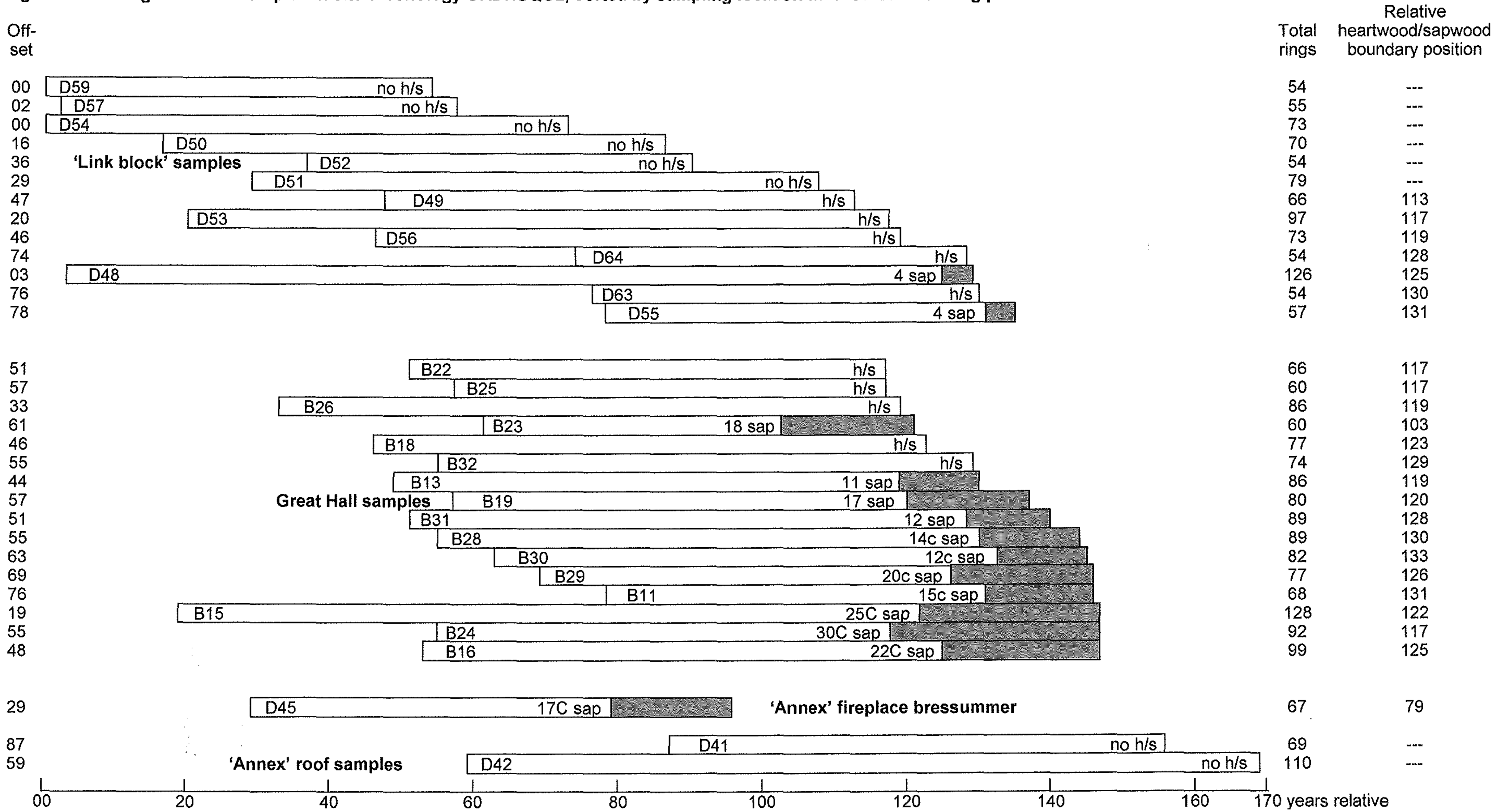


Figure 8: Bar diagram of the samples in site chronology ORDHSQ01



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Figure 9: Bar diagram of the samples in site chronology ORDHSQO2, sorted by sampling location in last measured ring position



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample, the last measured ring date is the felling date of the timber
c = complete sapwood on sample, all or part lost during sampling

Figure 10: Bar diagram of the samples in site chronology ORDHSQ03

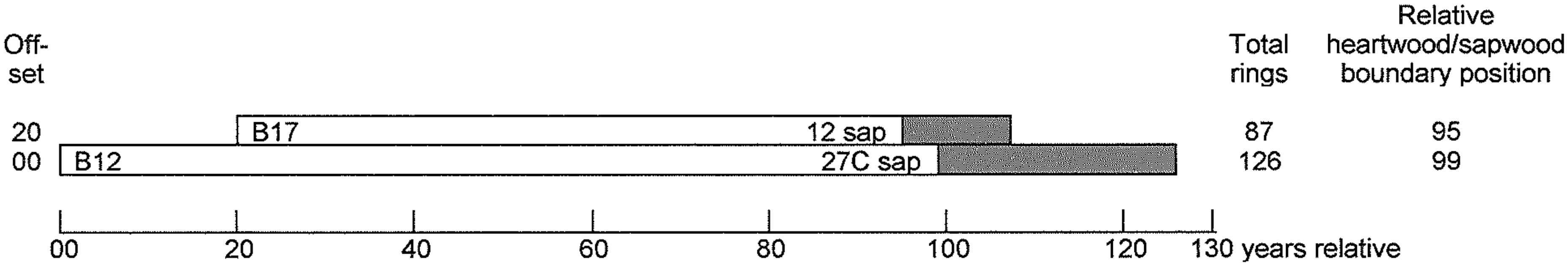
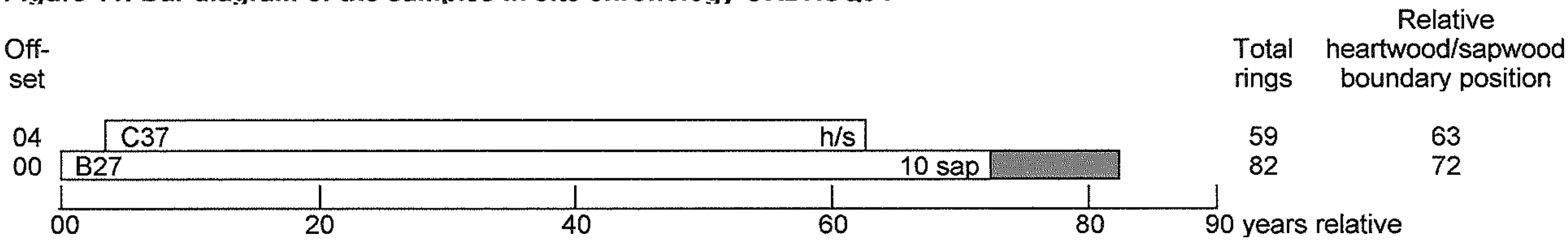


Figure 11: Bar diagram of the samples in site chronology ORDHSQ04



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample.

Figure 12: Bar diagram of the samples in site chronology ORDHSQ05

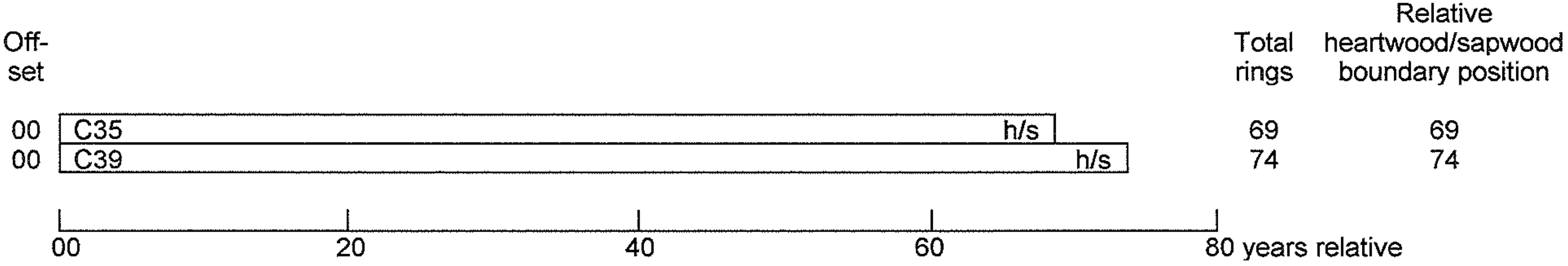
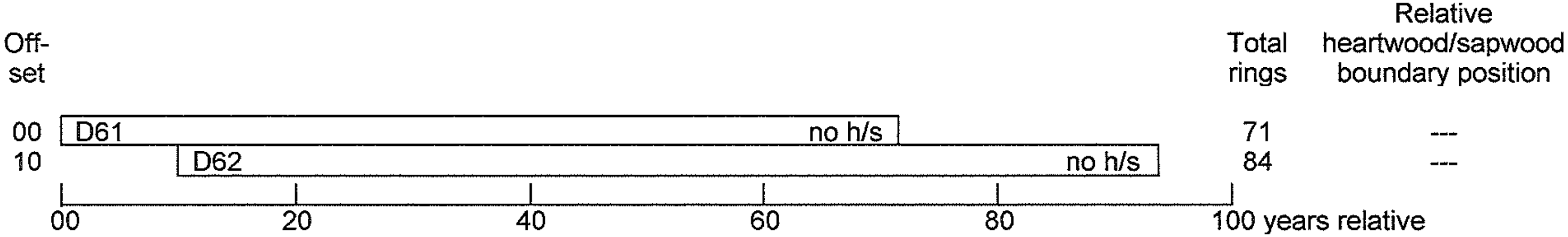


Figure 13: Bar diagram of the samples in site chronology ORDHSQ06



white bars = heartwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Data of measured samples – measurements in 0.01 mm units

ORD-A01A 60
97 190 173 173 160 158 132 137 133 171 129 201 178 165 145 205 155 169 102 138
135 111 79 81 42 55 77 53 79 73 81 67 100 74 69 84 68 97 91 33
41 38 26 15 19 27 18 15 49 47 23 21 20 29 25 34 51 37 34 31
ORD-A01B 60
118 185 188 176 170 176 86 123 192 162 125 202 157 179 152 205 159 172 103 135
143 115 81 85 64 53 80 81 72 85 67 75 81 76 100 86 70 102 86 42
49 42 21 14 20 20 24 36 42 36 34 30 29 32 38 35 37 37 33 27
ORD-A02A 180
99 137 191 130 98 98 148 125 113 119 96 104 144 142 117 125 122 115 97 106
114 114 83 86 104 127 178 127 90 124 94 87 104 88 81 125 129 115 72 73
135 102 98 145 130 65 90 122 133 118 90 163 129 62 62 108 191 129 119 122
88 97 124 160 131 102 90 112 106 99 145 137 166 153 201 190 102 106 159 125
139 134 150 161 114 78 73 71 93 80 106 99 134 88 120 87 119 77 104 65
89 76 90 108 76 63 96 75 76 70 70 74 66 58 60 76 61 76 87 74
58 73 58 54 74 67 72 69 55 59 61 58 50 60 57 62 76 50 54 49
45 28 38 31 27 40 37 42 48 50 46 37 44 27 38 36 27 38 38 48
36 47 52 41 59 45 38 51 53 52 62 62 100 58 65 71 81 73 65 87
ORD-A02B 200
134 115 70 94 123 89 99 93 131 112 87 84 77 132 143 123 72 80 115 133
108 131 185 129 97 102 147 127 127 126 90 113 140 144 122 134 115 113 103 100
114 110 85 82 93 125 175 125 89 122 89 91 103 93 82 126 127 118 75 81
131 108 94 147 132 59 92 123 127 118 84 160 143 65 68 105 193 120 131 122
86 105 119 147 138 101 91 107 106 110 133 140 159 158 201 189 95 110 157 128
134 148 131 158 105 82 74 76 84 89 102 96 122 101 116 78 127 80 111 71
88 74 93 102 87 54 102 66 83 74 69 73 58 62 73 69 60 72 99 66
61 76 66 57 71 62 76 58 65 69 58 58 55 62 53 68 68 57 52 53
41 34 45 23 28 39 41 49 34 50 36 37 40 38 40 35 28 34 36 51
32 51 49 45 50 49 45 37 62 50 68 59 105 63 61 74 73 80 62 80
ORD-A03A 194
137 135 119 122 145 121 167 149 143 170 188 190 171 145 93 165 166 173 127 153
146 162 166 113 168 140 177 125 187 163 148 142 206 153 99 107 141 103 92 133
114 99 94 71 97 68 102 94 95 82 85 109 51 54 37 26 26 27 27 36
35 23 31 34 49 40 57 44 67 95 86 49 51 48 53 78 70 55 57 66
65 58 75 57 48 56 45 44 45 47 41 47 61 61 70 64 69 79 71 61
73 41 73 84 74 74 70 54 80 77 65 88 54 46 65 109 84 93 60 92
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111 78 93 90 126 107 104 138 102 107 68 98 76 82 80 64 77 64 87 102
86 81 92 129 108 95 74 76 111 99 120 128 58 57 59 53 74 69 66 101
65 72 74 109 62 104 77 91 89 90 88 87 81 82
ORD-A03B 190
147 137 124 123 156 121 161 153 146 177 185 201 159 144 92 156 168 183 114 170
150 159 169 108 168 143 181 122 195 151 148 144 205 152 92 106 144 106 97 135
108 104 84 71 98 70 96 106 90 66 93 102 51 41 37 28 27 28 28 34
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78 41 76 88 74 75 70 56 78 77 61 93 52 47 70 104 81 97 54 88
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71 73 68 94 70 108 85 87 94 94

ORD-A04A 147
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87 78 79 120 82 94 95 75 89 118 125 127 149 120 131 124 108 120 102 131
117 137 127 123 136 150 175
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47 68 67 103 74 73 73 67 69 40 27 43 52 51 69 89 61 67 84 105
83 82 75 62 52 39 67 64 71 87 70 47 60 76 69 83 68 40 48 57
101 84 93 93 71 80 68 73 86 63 77 76 101 101 77 105 106 82 94 88
64 79 102 94 93 99 94 128 96 118 114 113 123 115 100 142 114 104 110 107
90 77 92 124 80 91 103 74 85 105 131 128 146 123 127 123 120 115 104 130
117 148 131 124 144 146 163
ORD-A05A 93
203 143 144 156 114 106 92 68 80 98 149 148 151 157 134 204 187 185 171 133
168 169 156 159 199 176 130 125 179 168 122 159 163 169 172 174 176 158 167 167
145 139 117 141 136 111 132 125 140 127 120 124 125 118 125 110 118 123 117 136
134 94 133 104 112 131 117 90 123 133 121 130 118 127 99 91 85 78 95 65
56 62 41 59 61 77 82 57 62 74 69 65 61
ORD-A05B 93
186 144 141 164 110 99 83 77 80 99 144 136 153 157 141 196 184 196 168 150
193 163 161 165 184 170 139 140 193 180 127 166 143 172 173 164 163 171 165 158
152 130 117 143 134 116 127 130 138 132 118 112 123 116 138 106 117 122 132 147
107 115 112 103 120 122 106 110 111 139 132 123 109 130 98 93 81 84 89 77
50 58 47 51 63 78 72 72 58 72 63 67 76
ORD-A06A 167
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33 39 31 53 31 24 22 31 36 39 25 38 38 22 31 26 31 36 62 81
57 44 46 25 40 60 104 104 93 78 74 70 69 53 44 45 67 62 89 104
89 67 83 93 93 89 80 70 100 52 65 59 61 60 60 48 54 73 68 65
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96 75 93 62 63 65 88 81 75 76 81 121 88 108 94 113 114 122 118 123
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125 108 104 98 94 134 116 100 102 124 138 122 138 121 131 78 80 54 70 65
52 59 86 115 104 88 87
ORD-A06B 167
65 65 62 41 42 48 65 73 68 53 40 44 43 41 24 29 42 41 35 37
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103 131 110 103 99 76 93 116 77 99 93 70 92 100 132 132 149 126 116 137
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57 57 79 121 106 88 95
ORD-A07A 177
118 106 85 62 61 58 72 98 72 62 73 69 59 56 55 66 63 80 74 86
65 76 68 77 65 62 79 76 66 75 70 62 44 40 41 41 45 41 48 43
41 45 66 54 63 63 74 49 69 71 100 74 93 129 81 111 99 95 118 129
141 116 120 161 139 140 197 220 209 173 124 130 196 201 192 166 205 176 162 157

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.

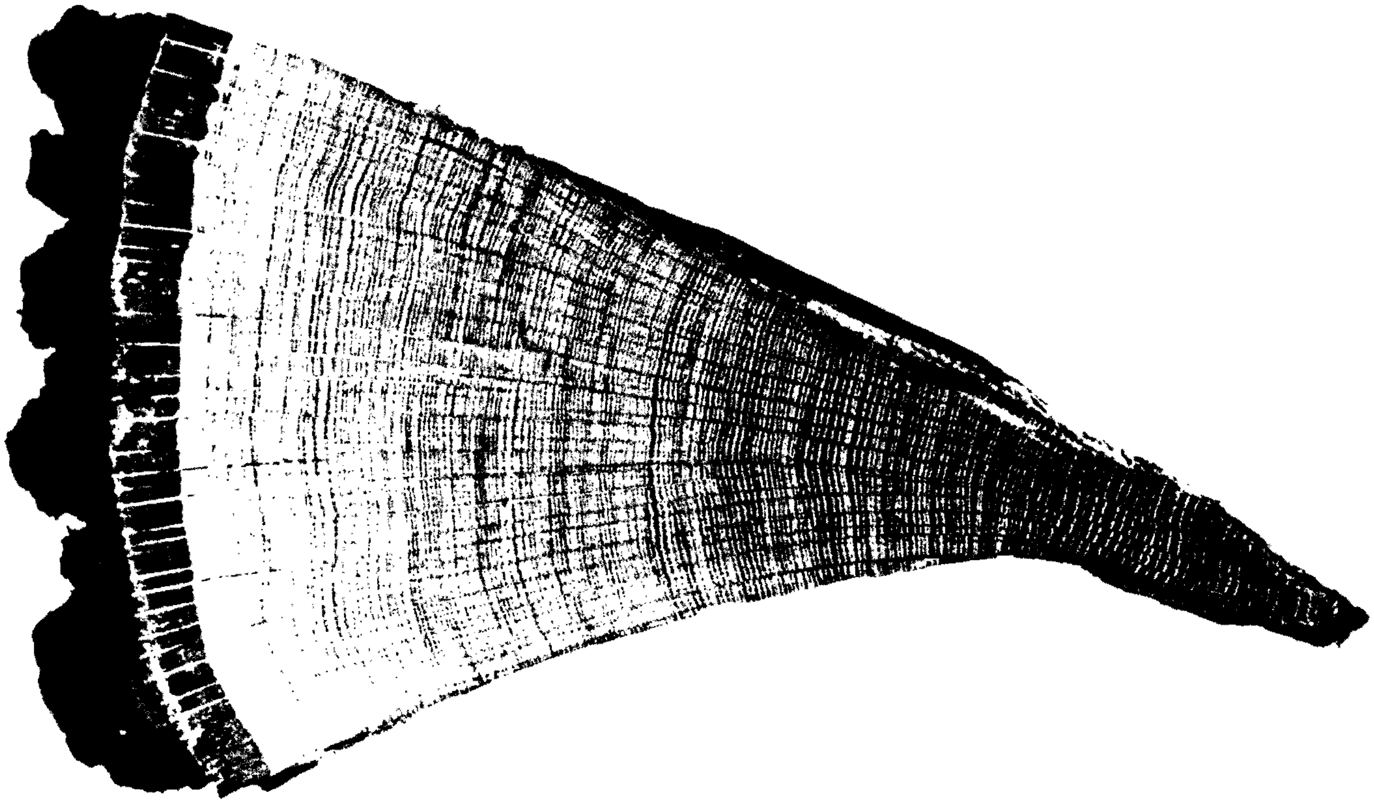


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

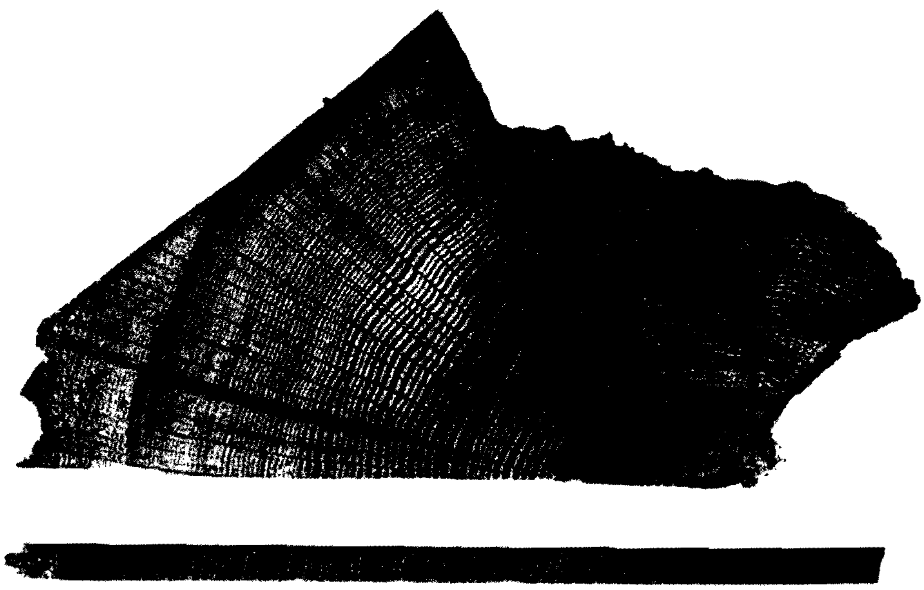


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

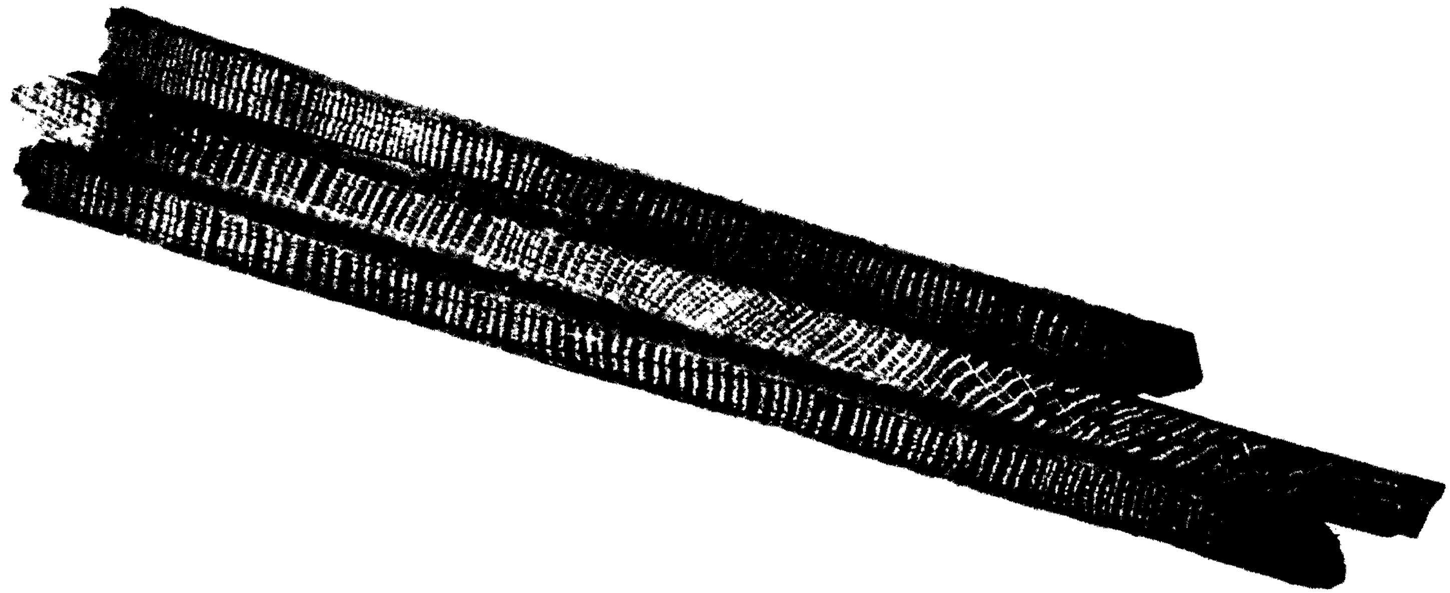


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

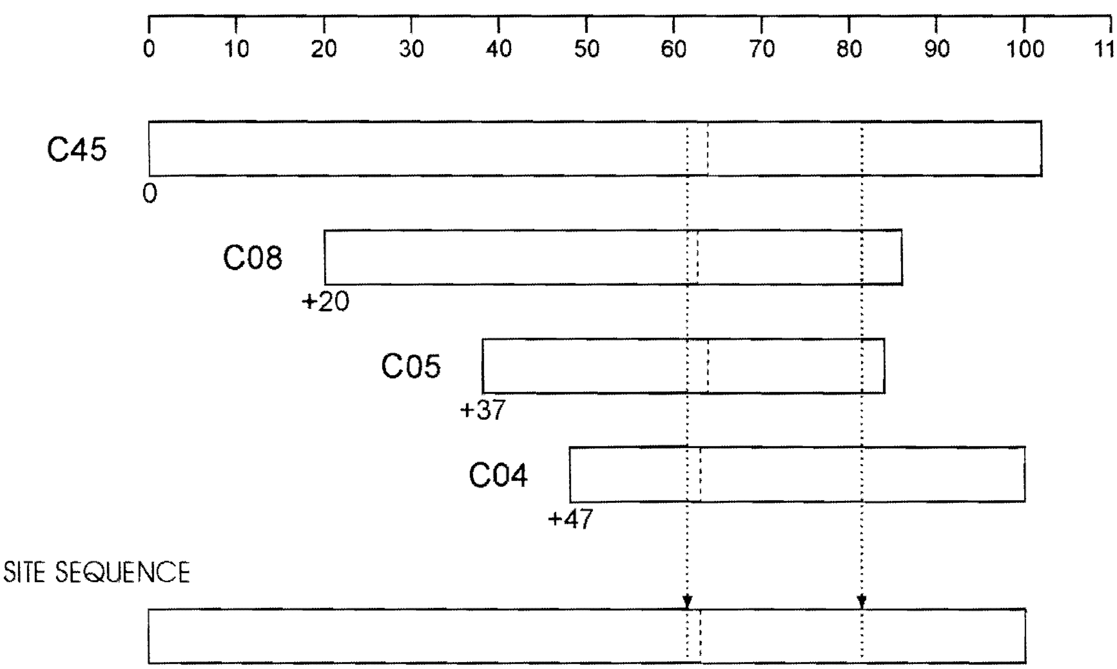


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

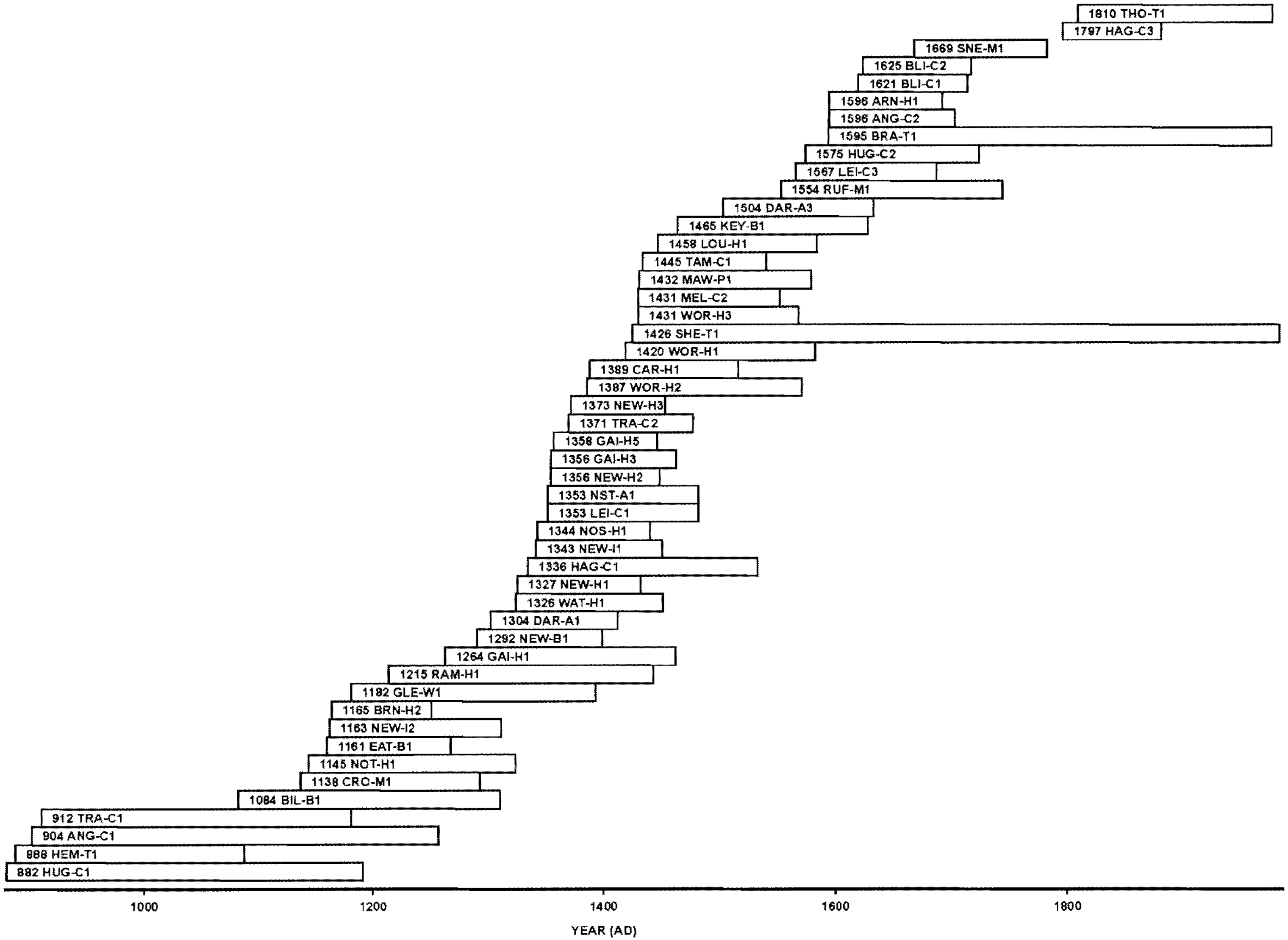
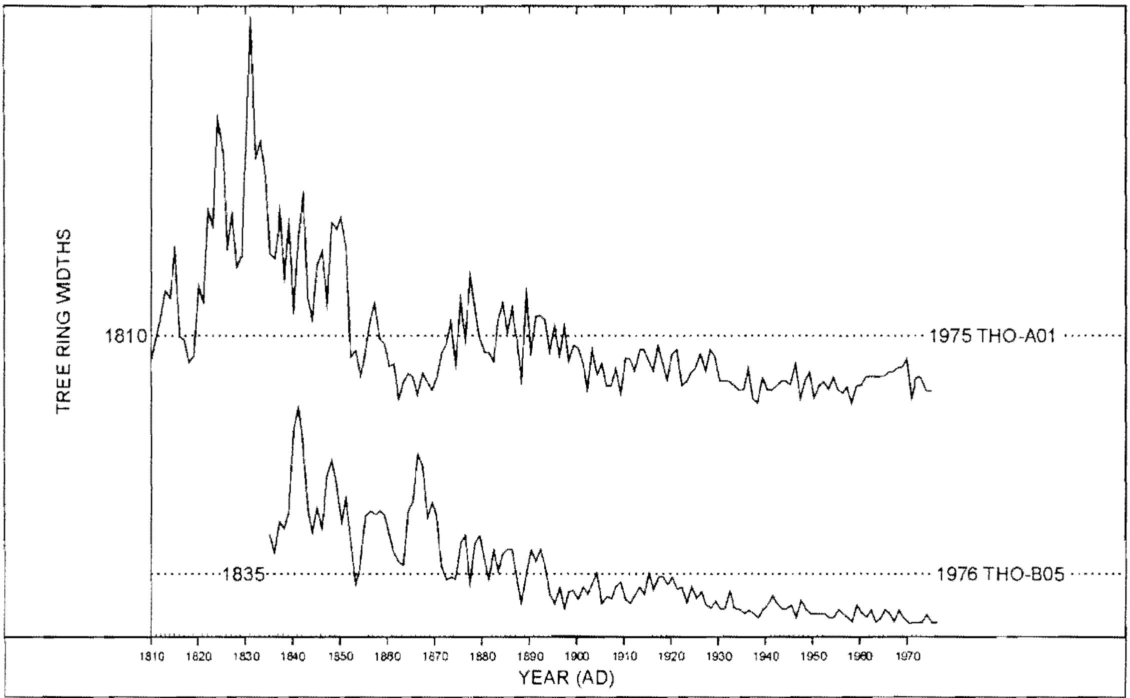


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

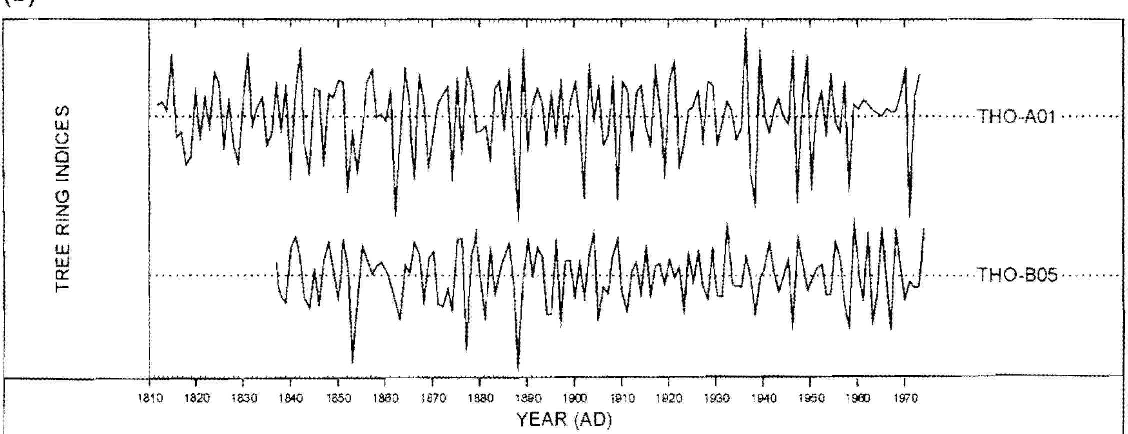


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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