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8-9, 9A, AND THE LAW LIBRARY, THE CLOSE, EXETER, DEVON

TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Interpretation of the sapwood on the dated samples indicates that the timbers of both the roof and floor of 8-9 The Close (the front range) were cut as part of a single felling operation in the period AD 1402–27, with the timbers of roof 2 of 9a The Close (the north end of the rear east range) felled AD 1406–31. It is possible, therefore, that these two roofs, and roof 1 (at the south end of the rear east range, and structurally earlier than roof 2), are all co-eval.

Two dated timbers from the roof of the Law Library (the rear west range) have an estimated felling date in the period AD 1417–42, suggesting that this part of the complex might be very slightly later.

One timber from roof 1 of 9a The Close has an estimated felling date of AD 1468–93 and probably represents a repair phase.

Thus, while there may have been breaks, it is possible that this whole complex was constructed as part of a single, extended, work programme dating to the early-fifteenth century.

Five other, site chronologies and 19 individual samples remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

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Historic Environment Service
Matford Offices
County Hall
Exeter EX2 4QW

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CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
0115 960 3833
roberthoward@tree-ringdating.co.uk
alison arnold@tree-ringdating.co.uk

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INTRODUCTION

This complex of buildings under investigation is located on The Close in Exeter (SX 921 926; Figs 1 and 2). Number 8-9 forms a broad front range facing south onto Cathedral Green, whilst two additional ranges run from the rear of this front range at obtuse angles (Fig 3). The rear range at the east end forms 9a The Close, whilst the rear range at the west end is known as the Law Library. Together the three ranges thus almost enclose a small, elongated, courtyard (Figs 3 and 4).

The following paragraphs are based mainly on on-site observation with input from Richard Parker, John Allan and Stuart Blaylock all at the time from Exeter Archaeology.

The front range, 8-9 The Close, is of two storeys, coursed in Heavitree stone to the ground floor, with a wide, decorated, arched passageway at its west end (Fig 5). The half-timbered upper floor over-sails the lower, being supported on curved oak brackets resting on stone corbels. The roof of the front range is of comparatively plain principal rafter trusses with collars and arch-braces, the principals carrying double through-purlins. All such timbers are lightly carved with shallow roll-mouldings. Although no date has been ascribed to this range, it is thought to be late-medieval.

The roof to the rear east range, 9a The Close, appears to be of two distinct parts. Roof 1, at the southern end of this range, is of four bays formed by three open trusses, with a fourth closed truss at the north end forming the boundary with roof 2, which lies further north still. The three open trusses have straight collars with the collar to the fourth, end, truss being cranked. The collars are supported by chamfered arch braces. Roof 2 is a simpler, two-and-a-half bay structure, now somewhat altered from its original form. This roof is formed by two principal rafter trusses with double purlins and the north gable wall. Redundant mortices indicate the existence of former collars. The date of these roofs is unknown.

The rear west range, the Law Library, contains a three-bay open hall formed by four single hammer beam roof trusses of a design similar to that of Westminster Hall. Between the main trusses there are intermediate frames. The hammer-beams, arch-braces, coved rafters, and purlins, along with many other elements, are all highly moulded and carved, as is the open-work tracery in-fill. The ends of the hammer beams are decorated with angels, whilst ornately carved bosses hide the joints between timbers (Fig 6a/b). The roof is thus exceptionally decorative, even by the standards of the Exeter group, of which other examples include The Archdeacon's House, The Guildhall, and The Deanery (Howard *et al* 1999a, 1999b, 2000). The Law Library is believed to date to *c* AD 1450-AD 1550, but a date as early as *c* AD 1390 has also been suggested.

The structural relationship of the roofs suggests that roof 1 of number 9a (rear east range) is either coeval with, or possibly slightly later than, that of 8-9 (the front range). The ridge of roof 1 extends into the roof space of the front range, and the ragged nature of the wall-top at the back of the front range here would not be expected if it originally formed an outside wall, as would be the case if it were built as a discrete and separate structure, although it might be explicable if it this part of the wall was never intended to be visible, being hidden by a roof. The rear slope of the front range might also have survived here had it been built separately. It appears that, in turn, roof 2 of number 9a was added to roof 1, the upper purlins of roof 2 being neatly cut into the principal rafters of truss 1 (the closed truss) of roof 1. Again this second roof might possibly have been added almost immediately, but also, possibly, some time later.

It is believed that the front range and the open hall of the Law Library once comprised the Canon's House, access between these two parts being via an ornately carved multi-cusped and foiled doorway in a now-blocked partition wall (Fig 7).

SAMPLING

Tree-ring dating of timbers from both 8-9 The Close and from the roof of the Law Library has been attempted in the past, but without great success (Howard *et al* 2000). This was in some measure due to the difficulty of accessing the roof of the Law Library and obtaining sufficient suitable samples, a consequence of this part of the building once being used as office space, and in part due to the paucity at that time of relevant reference material with which site data could be compared. Since 2008, however, a sequence of building developments and alterations has taken place, allowing greater access not only to the Law Library, but also, gradually, to different parts of number 9a, particularly the rear east range and its previously inaccessible roof timbers. Furthermore, not only has the amount of tree-ring reference material greatly increased over the intervening years, but the complex has benefited from further survey and recording (Allan and Ives 2007, Parker 2009) adding to that undertaken previously by Thorp and Brown (1979).

Sampling and analysis by tree-ring dating of timbers from the three constituent parts of this building complex, 8-9 The Close, 9a The Close, and the Law Library, were commissioned by English Heritage. Apart from the roof timbers of each part, this programme of analysis was to include a series of joists to the ground-floor ceiling of the front range, both those always exposed in the external west passageway and those exposed by the lifting of a small number of first-floor floorboards during internal renovation works. The sampling and analysis of a small section of wall panelling temporarily removed from the front range during repairs was also requested (Fig 8).

The purpose of this analysis was to establish a date for the various elements of the building and to more accurately place the roofs, for comparative purposes, within the context of a group of similar roofs in Exeter and the surrounding region. This research into the Exeter roofs has been undertaken in connection with a major programme of recording and repair at Bowhill in Devon, which was being funded by English Heritage (Blaylock 2004).

A further purpose of the original sampling was to obtain additional tree-ring data for this area. Although in recent years, as a consequence of English Heritage funded work, Exeter itself has provided a number of well-replicated and dated site chronologies, the south-west in general still remains relatively under-represented. This is in part due to the fact that samples obtained in this area frequently have relatively few rings. This is a result of relatively rapid growth of the trees and their subsequent use whilst still relatively young; such trees producing timbers with either too few rings or only borderline suitability for analysis. It was believed that this complex of buildings, which contain a substantial amount of timber, provided an opportunity to produce a long and well-replicated site chronology. This would therefore add to the localised network of reference material available and hence aid the dating of sites in this sometimes problematic area in future studies.

Thus, from the material exposed during the various stages of building and alteration work here, a total of 80 samples was obtained. Each sample was given the code EXT-D (for Exeter, site "D"), and numbered between 01 and 93. Gaps were intentionally left in the sequence of sample numbers to allow for the possibility that additional timbers might subsequently become available in certain parts of the complex should further repair work have been undertaken in an area already sampled.

A total of 24 samples, EXT-D01–24, was obtained by coring the roof timbers of numbers 8-9 The Close, with a further four cores, EXT-D25–28, being obtained from the common joists of the ground-floor ceiling of the passageway. Four cores, EXT-D30-33, were obtained from the principal beams of the ground-floor ceiling (Figs 9a–e).

In addition using an eye-piece with graticule, an attempt was also made to obtain ring-width measurements from the prepared edges of six oak wall panels removed from their fixings during repairs to this front range, these being designated as samples EXT-D41–47 (Fig 9f).

A total of 18 samples, EXT-D51–68, was obtained from the roof timbers of the Law Library (Figs 10a–d), with a further 23 samples being obtained from number 9a, EXT-D71–85, from roof 2 at the northern end of number 9a (Figs 11a–c) and EXT-D86–93 from roof 1 at the south end of number 9a (Figs 11a, and 11d-e). It should be pointed out, however, that in an attempt to obtain the maximum number of rings from one particular timber, it was cored twice, firstly as EXT-D75 and again as EXT-D79, as more of the timber was revealed during building works. Given that the two samples do not overlap with each other sufficiently to cross-match, they were retained as two individual samples.

The plans and drawings (Figs 9a–11e) on which the positions of the cores were recorded at the time of sampling, where possible, were obtained from either Exeter Archaeology or the archives of the Ministry of Works, Ancient Monument Branch. Details of the samples are given in Table 1. In this table the trusses, frames, and other timbers are numbered following the schema on the drawings provided and further identified on a north-south or east-west basis as appropriate.

ANALYSIS

Each of the core samples obtained was prepared by sanding and polishing. It was seen at this time that 14 of these had fewer than the minimum of 54 rings necessary for reliable dating, and these were rejected as being unsuitable.

In addition, due to the nature of the material, presenting as it did narrow growth rings on thin, non-radially split, boards with the ring sequence consequently being broken into segments by the medullary rays, it was impossible, to obtain reliable measurements from the prepared edges of the six oak wall panels. Given this uncertainty, the data is not included in this report and the samples are listed in Table 1 as being unmeasured.

The growth-ring widths of the remaining 59 cores were, however, measured, these data then being compared with each other by the Litton/Zainodin grouping procedure (see Appendix). The ring width data are given at the end of this report. By this comparative process, seven different groups, accounting for 40 samples, could be formed, the samples of each group cross-matching at the relative positions shown in the bar diagrams, Figures 12–18.

The samples of each cross-matching group were combined at the indicated off-set positions to form site chronologies EXTDSQ01–SQ07. Each site chronology was then compared with the remaining 19 individual ungrouped samples but there was no further reliable cross-matching. Each of the seven site chronologies was then compared with a full range of reference chronologies for oak, this indicating a cross-match and date for two of these. The first dated site chronology EXTDSQ01 accounts for 26 measured samples, 15 of them from the front range, 8-9 The Close, nine of them from roof 2 of number 9a, and two of them from the Law Library. This site chronology has 199 rings spanning the years AD 1208–1406; the evidence for this dating is given in the *t*-values of Table 2.

The second dated site chronology EXTDSQ07 accounts for two measured samples, both from roof 1(the rear east range roof) of 9a. This site chronology has 94 rings spanning the years AD 1346–1439; the evidence for this dating is given in the *t*-values of Table 3.

Site chronologies EXTDSQ02–SQ06 comprise three, three, two, two, and two samples each. In length these site chronologies range from 55 to 108 rings; none of these site chronologies can be dated.

Each of the 19 measured but ungrouped samples was than compared individually with the full range of reference chronologies for the oak, but again there was no satisfactory cross-matching, and these samples must also remain undated.

This analysis can be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span (where dated)
EXTDSQ01	26	199	AD 1208-1406
EXTDSQ02	3	108	undated
EXTDSQ03	3	80	undated
EXTDSQ04	2	80	undated
EXTDSQ05	2	68	undated
EXTDSQ06	2	55	undated
EXTDSQ07	2	94	1346-1439
Undated singles	19	---	undated
Unmeasured	21	---	---

INTERPRETATION AND DISCUSSION

None of the 26 dated samples in site chronology EXTDSQ01 retains complete sapwood and it is thus not possible to give a precise felling date for any of the timbers represented, although it is clear that all are broadly coeval. Thirteen of these 26 samples do, however, retain the heartwood/sapwood boundary, that is, only the sapwood rings of the trees are missing, and it is thus possible to give an estimated likely felling date range for these timbers.

As may be seen from Table 1 and the bar diagram, Figure 12, where the cross-matching samples of dated site chronology EXTDSQ01 are shown sorted by sample location and in last measured ring date order, the overall position of the heartwood/sapwood boundary varies by some 26 years. The earliest sapwood boundary is a relative position 173 (AD 1380), on sample EXT-D03, with the latest boundary being at relative position 199 (AD 1406) on sample EXT-D86. This variation is possibly slightly wider than might be expected in a group of timbers were they all cut at the same time as each other in a single episode of felling, but might be explicable in timbers felled over a period of time. In respect of this possibility, it may be of interest to note that if the samples are examined by area group, a slight difference in felling date range may be detected. Although this dating would support the relative sequence of building construction as intimated by the structural evidence, because the date ranges have a significant overlap, this does not necessarily indicate that the two parts of the building are definitely of different construction dates.

The potentially earliest phase of felling appears to be represented by the roof and first-floor timbers of the front range, numbers 8-9 The Close (samples EXT-D01-33), the portion which structurally appears to precede by some unknown time the building of the rear east range, number 9a. Within this sub-group the sapwood boundary varies by only 11 years from relative position 173 (AD 1380), on sample EXT-D03 to relative position 184 (AD 1391) on sample EXT-D19, such a limited variation being consistent in representing a group of timbers felled at the same time as each other. The average date of the boundary on the six samples in this sub-group where it exists is AD 1387. Using a 95% confidence limit of 15–40 rings for the amount of sapwood these trees might have had would give the timbers represented an estimated felling date in the range AD 1402–27.

A second, potentially slightly later, phase of felling appears to be represented by the timbers of roof 2 of the rear east range, number 9a (samples EXT-D71–85), a portion that is, structurally, believed to post-date the building of the front range. Within this sub-group the sapwood boundary varies by 24 years from relative position 175 (AD 1382), on samples EXT-D79 and D80, to relative position 199 (AD 1406) on sample EXT-D86. The average date of the boundary on the five samples in this sub-group where it exists is slightly later at AD 1391. Using again a 95% confidence limit of 15–40 rings for the amount of sapwood these trees might have had would give the timbers represented an estimated felling date in the range AD 1406–31, though given the variation in heartwood/sapwood boundary date these timbers could possibly have been felled over a period of a few years.

A possible further phase of felling is represented by two dated samples, EXT-D53 and D56, from the Law Library roof. Both these samples retain the heartwood/sapwood boundary, dated in each case to AD 1402. Using the same sapwood estimate as above, 15–40 rings, would give the timbers represented an estimated felling date in the range AD 1417–42.

It may be seen therefore, that although the exact felling date of none of the timbers can be determined, the estimated felling date ranges for the various groups are very similar, and certainly overlap with each other to a considerable degree. This would suggest that although the timbers may not all have been felled at exactly the same time as each other, they are likely to have been felled over a fairly short period.

Thirteen other dated samples in site chronology EXTDSQ01 do not have the heartwood/sapwood boundary and it is thus not possible to be completely certain that they too were definitely cut as part of their respective building sequence. However, such is the level of cross-matching between some of these samples and those with the heartwood/sapwood boundary that it is likely that all the trees represented by this group were growing close together in the same copse or stand of woodland. The trees they represent, therefore, are more likely to have been felled at the same or very similar times rather than being felled at different times yet still being used in the same part of the building. There is, for example, a cross-match with a value of t=8.0 between sample EXT-D06, which is *sans* heartwood/sapwood boundary and sample EXT-D18, on which it is present, or similarly samples EXT-D26 and D27 which cross-match with a value of t=7.6. Likewise at match with a value of t=5.9 is found between sample EXT-D12 (no sapwood boundary) and D15 (sapwood boundary), the value probably representing trees from at least the same woodland area. There is, in any case, no evidence on any of the timbers themselves of reuse, such as redundant mortices or peg holes, and it is thus almost certain that all the dated timbers of each part of the building were felled at the same time.

Two samples, EXT-D89 and D91, respectively from a common rafter and purlin of roof 1 of number 9a, have been dated as site chronology EXTDSQ07. Although, because of compaction to its outer rings, the heartwood/sapwood boundary is not included in the measured portion of sample EXT-D91, this is in fact present on the core, approximately 15 rings later than the last ring which has been measured. Given that this last measured ring is dated to AD 1438, the heartwood/sapwood boundary itself would be dated *circa* AD1453. Using the usual sapwood estimate of 15–40 rings, would give this timber an estimated felling date of *circa* AD 1468–93.

The other sample in site chronology EXTDSQ07, EXT-D89, does not have the heartwood/sapwood boundary and the felling date of the timber this represents cannot thus be determined. However, with a last measured, heartwood, ring date of 1439, this is unlikely to be before AD 1455, this date being based on a 95% limit of a minimum of 15 sapwood rings. As such these two timbers are later than the majority of others which have been dated, and may be explicable as being later repairs.

Felling date ranges or felled-after dates cannot of course be given for any of the trees represented by the samples of the undated site chronologies. However, judging by the relative position of the heartwood/sapwood boundary on them, some of these undated samples probably also represent trees felled at the same, unknown, time as each other. Those represented by samples EXT-D09, D10, and D11 (Fig 14), samples EXT-D02 and D07 (Fig 17), and those from which samples EXT-D52 and D60 (Fig 13) have been obtained, being examples.

CONCLUSION

Analysis by dendrochronology of 59 samples from timbers in three different parts of this building complex has produced seven site chronologies. Only two of these seven, site chronologies EXTDSQ01 comprising 26 samples, and site chronology EXTDSQ07, accounting for two samples can be dated.

Interpretation of the sapwood on the dated samples indicates the probability that the timbers of both the roof and floor of 8-9 The Close (the front range) were cut as part of a single felling operation some time in the period AD 1402–27, with the timbers of roof 2 of 9a The Close (the rear east range) having an estimated felling date in the period AD 1406–31. Two dated timbers from the roof of the Law Library (the rear west range) have an estimated felling date in the period AD 1417–42. One timber from roof 1 of 9a The Close has an estimated felling date of AD 1468–93.

Despite the imprecision of this dating, it would appear that this whole complex dates to the early-fifteenth century, and that, although possibly built in stages, it may all have been envisioned as a single programme of construction, with relatively little time between one stage and another. It would appear that later repairs were made using later-fifteenth century timbers.

The results make an important contribution to the interpretation of this complex of buildings, showing that the front range, and the form of its roof, is neither as late as was generally believed, nor quite as early as was possibly proposed. The building is thus now set within the context of similar early-fifteenth century buildings in urban Exeter, including the Archdeacon's House and the Deanery.

In this context it may be of interest to note that the level of cross-matching found between the samples of the building analysed here is repeated, particularly amongst the samples of both the Archdeacon's House and the Deanery, Exeter. Both these buildings have been dated by dendrochronology to the early-fifteenth century. In these two latter cases, as here, whilst some samples cross-match with each other very well, suggesting that some of the trees used in each building have come from the same source, and although the overall cross-matching within the groups of samples from each building is usually satisfactory overall, the individual cross-matches are sometimes low, though satisfactory, and there are many samples which either do not cross-match with any others, or if they do form groups, the groups contain few samples and they remain undated.

Taken all together this may suggest that either the supply of timbers from any one source near Exeter was limited in the early-fifteenth century, leading to the timbers having to be found from many different places with a resultant greater than normal variation in the tree-ring patterns found within the buildings, or there is some peculiarity about the growth regime of fourteenth-century trees in the area resulting in them having an unusual growth pattern. The samples themselves, however, show no peculiarities such as compressed, distorted, or indistinct rings suggesting anything unusual about their growth.

Judging by the *t*-values given in Table 2, which lists some of the reference chronologies with which site chronology EXTDSQ01 has been cross-matched and dated, there is a general impression that the timbers represented have come from a relatively local source or sources. The later-fifteenth century timber represented by site chronology EXTDSQ07 and used for what appears to be a repair to roof 1 of 9a, is probably from a different woodland, and possibly sourced from further afield.

As intimated above, some of the samples represent trees growing close together, perhaps in the same copse and certainly very likely within the same woodland. It is possible, however, that some timbers might indeed be derived from the same tree, those represented by samples EXT-D09, D10, and D11, which cross-matching with values between in excess of t=11.0 to higher than t=14.0.

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TABLES

Table 1: Details of samples from 8-9, The Close, 9a The Close, and the Law Library, Exeter, Devon

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
	8-9 The Close (front range) roof timbers					
EXT-D01	South principal rafter, truss 4	54	no h/s	------	------	------
EXT-D02	Collar, truss 4	54	no h/s	------	------	------
EXT-D03	South principal rafter, truss 5	103	h/s	1278	1380	1380
EXT-D04	North principal rafter, truss 5	99	no h/s	------	------	------
EXT-D05	South principal rafter, truss 6	146	h/s	1246	1391	1391
EXT-D06	North principal rafter, truss 6	122	no h/s	1251	------	1372
EXT-D07	Collar, truss 6	54	h/s	------	------	------
EXT-D08	South upper purlin, truss 5-6	54	h/s	------	------	------
EXT-D09	North upper purlin, truss 5-6	80	h/s	------	------	------
EXT-D10	South common rafter 1, truss 5-6	56	no h/s	------	------	------
EXT-D11	North common rafter 3, truss 5-6	75	h/s	------	------	------
EXT-D12	South upper purlin, truss 8-9	119	no h/s	1222	------	1340
EXT-D13	South upper purlin, truss 9-10	67	no h/s	1208	------	1274
EXT-D14	North upper purlin, truss 9-10	54	no h/s	1307	------	1360
EXT-D15	South common rafter 3, truss 2-3	122	h/s	1265	1386	1386
EXT-D16	South common rafter 4, truss 4-5	67	no h/s	1239	------	1305
EXT-D17	North upper archbrace, truss 5	69	no h/s	------	------	------
EXT-D18	North principal rafter, truss 8	157	h/s	1231	1387	1387
EXT-D19	South principal rafter, truss 8	99	h/s	1293	1391	1391
EXT-D20	North upper purlin, truss 8-9	128	no h/s	1251	------	1378
EXT-D21	North principal rafter, truss 9	60	3	------	------	------
EXT-D22	South lower arch brace, truss 9	58	4	------	------	------
EXT-D23	South principal rafter, truss 9	113	no h/s	1246	------	1358
EXT-D24	North principal rafter, truss 10	nm	---	------	------	------

Table 1: continued

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
	8-9 The Close, passageway ceiling					
EXT-D25	Joist 5	62	no h/s	------	------	------
EXT-D26	Joist 2	147	h/s	1242	1388	1388
EXT-D27	Joist 4	56	no h/s	1238	------	1293
EXT-D28	Joist 3	146	no h/s	1226	------	1371
	8-9 The Close , ground floor ceiling					
EXT-D30	Main west ceiling beam	nm	---	------	------	------
EXT-D31	Main east ceiling beam	nm	---	------	------	------
EXT-D32	Main east middle ceiling beam	nm	---	------	------	------
EXT-D33	Main west middle beam	57	h/s	------	------	------
	8-9 The Close , panels					
EXT-D41	Panel 14	nm	---	------	------	------
EXT-D42	Panel 13	nm	---	------	------	------
EXT-D43	Panel 17	nm	---	------	------	------
EXT-D44	Panel 16 (part 1 inner rings)	nm	---	------	------	------
EXT-D45	Panel 16 (part 2 outer rings)	nm	---	------	------	------
EXT-D46	Panel 18	nm	---	------	------	------
EXT-D47	Panel 15	nm	---	------	------	------

Table 1: continued

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
	Law Library (rear west range open hall)					
EXT-D51	North diagonal rib, east bay 1	79	no h/s	------	------	------
EXT-D52	Lower intermediate rafter, east bay 1	88	h/s	------	------	------
EXT-D53	South diagonal rib, east bay 1	54	h/s	1349	1402	1402
EXT-D54	North diagonal rib, west, bay 2	61	no h/s	------	------	------
EXT-D55	South diagonal rib, west, bay 2	62	no h/s	------	------	------
EXT-D56	Lower intermediate rafter, west bay 2	68	h/s	1335	1402	1402
EXT-D57	West archbrace, truss 1	80	no h/s	------	------	------
EXT-D58	West archbrace, truss 2	nm	---	------	------	------
EXT-D59	North diagonal rib, east bay 2	70	no h/s	------	------	------
EXT-D60	Lower intermediate rafter, east bay 2	77	h/s	------	------	------
EXT-D61	South diagonal rib, east bay 2	nm	---	------	------	------
EXT-D62	South archbrace, east bay 3	54	h/s	------	------	------
EXT-D63	Upper intermediate rafter, east bay 3	55	no h/s	------	------	------
EXT-D64	South diagonal rib, east bay 3	nm	---	------	------	------
EXT-D65	East upper architrave, truss 4	nm	---	------	------	------
EXT-D66	South archbrace, west bay 2	66	no h/s	------	------	------
EXT-D67	North archbrace, east bay 3	nm	---	------	------	------
EXT-D68	South archbrace, east bay 2	nm	---	------	------	------

Table 1: continued

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
	9a The Close (rear east range) roof 2					
EXT-D71	East upper purlin, truss A-B	108	no h/s	1267	------	1374
EXT-D72	East common rafter 7, truss A-B	62	h/s	1335	1396	1396
EXT-D73	West principal rafter, truss B	100	h/s	------	------	------
EXT-D74	East upper purlin, truss B-truss 1	nm	---	------	------	------
EXT-D75	West principal rafter, truss A (i, inner)	56	no h/s	1268	------	1323
EXT-D76	West common rafter 1, truss A-B	64	h/s	1343	1406	1406
EXT-D77	West common rafter 4, truss A-B	nm	---	------	------	------
EXT-D78	East principal rafter, truss B	70	no h/s	1272	------	1341
EXT-D79	West principal rafter, truss A (ii, outer)	87	h/s	1296	1382	1382
EXT-D80	East principal rafter, truss A	78	h/s	1305	1382	1382
EXT-D81	West common rafter 5, north end bay	60	h/s	------	------	------
EXT-D82	East common rafter 5, north end bay	76	no h/s	1270	------	1345
EXT-D83	West common rafter 4, north end bay	54	no h/s	------	------	------
EXT-D84	East common rafter 4, north end bay	55	no h/s	------	------	------
EXT-D85	East common rafter 3, north end bay	98	h/s	1293	1390	1390

Table 1: continued

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
	9a The Close (rear east range) roof 1					
EXT-D86	Middle west purlin, truss 3-4	nm	---	------	------	------
EXT-D87	West principal rafter, truss 1	54	h/s	------	------	------
EXT-D88	West common rafter 5, truss 2-3	63	h/s	------	------	------
EXT-D89	East common rafter 5, truss 3-4	94	no h/s	1346	------	1439
EXT-D90	East common rafter 6, truss 3-4	72	no h/s	------	------	------
EXT-D91	Middle east purlin, truss 2-3	75	no h/s	1364	------	1438
EXT-D92	Upper west purlin, truss 2-3	80	h/s	------	------	------
EXT-D93	Middle west purlin, truss 2-3	nm	---	------	------	------

*nm = not measured
**h/s = the heartwood/sapwood ring is the last ring on the sample
NB; Samples D75 and D79 are from the same timber: D91 has approximately 15 unmeasured rings to the heartwood/sapwood boundary

Table 2: Results of the cross-matching of site chronology EXTDSQ01 and relevant reference chronologies when first ring date is AD 1208 and last ring date is AD 1406

Reference chronology	Span of chronology	*t*-value	
Wadhayes, Awliscombe, Devon	AD 1179–1331	7.3	(Tyers *et al* forthcoming)
St Andrew's Church, Alwington, Devon	AD 1253–1391	7.3	(Arnold and Howard 2009)
St Mary the Virgin's Church, Yatton, Somerset	AD 1321–1400	6.7	(Wilson and Tyers 1999)
Kingswood, Glos (composite working mean)	AD 1191–1519	6.6	(Arnold and Howard 2004 unpubl)
Salisbury Cathedral spire and tower (sarum16), Wiltshire	AD 1229–1338	6.3	(Miles *et al* 2004)
The Deanery, Exeter Cathedral, Devon	AD 1233–1403	6.2	(Howard *et al* 2000)
Windsor Castle Round Tower, Berkshire	AD 1231–1354	6.1	(Haddon-Reece *et al* 1990)
Archdeacon's House, Exeter, Devon	AD 1186–1404	5.1	(Howard *et al* 1999)

Table 3: Results of the cross-matching of site chronology EXTDSQ07 and relevant reference chronologies when first ring date is AD 1346 and last ring date is AD 1439

Reference chronology	Span of chronology	*t*-value	
St Ciricus & St Julitta Church, St Veep, Cornwall	1352–1512	6.4	(Arnold *et al* 2005)
Prowse barn, Sandford, Devon	1380–1473	6.3	(Groves 2005)
40 Broad Street, Leominster, Herefordshire	1338–1499	6.2	(Miles 2001)
All Saints Church, Knipton, Leicestershire	1348–1488	6.2	(Arnold *et al* 2005)
Sinai Park, near Burton, Staffordshire	1227–1750	5.8	(Tyers 1997)
The Cottage, Charlwood, Surrey	1288–1406	5.7	(Miles and Worthington 2001)
Bridford Barton, Bridford, Devon	1281–1474	5.6	(Tyers *et al* forthcoming)
The Commandery, Worcester, Worcestershire	1284–1473	5.5	(Arnold *et al* 2006)

FIGURES

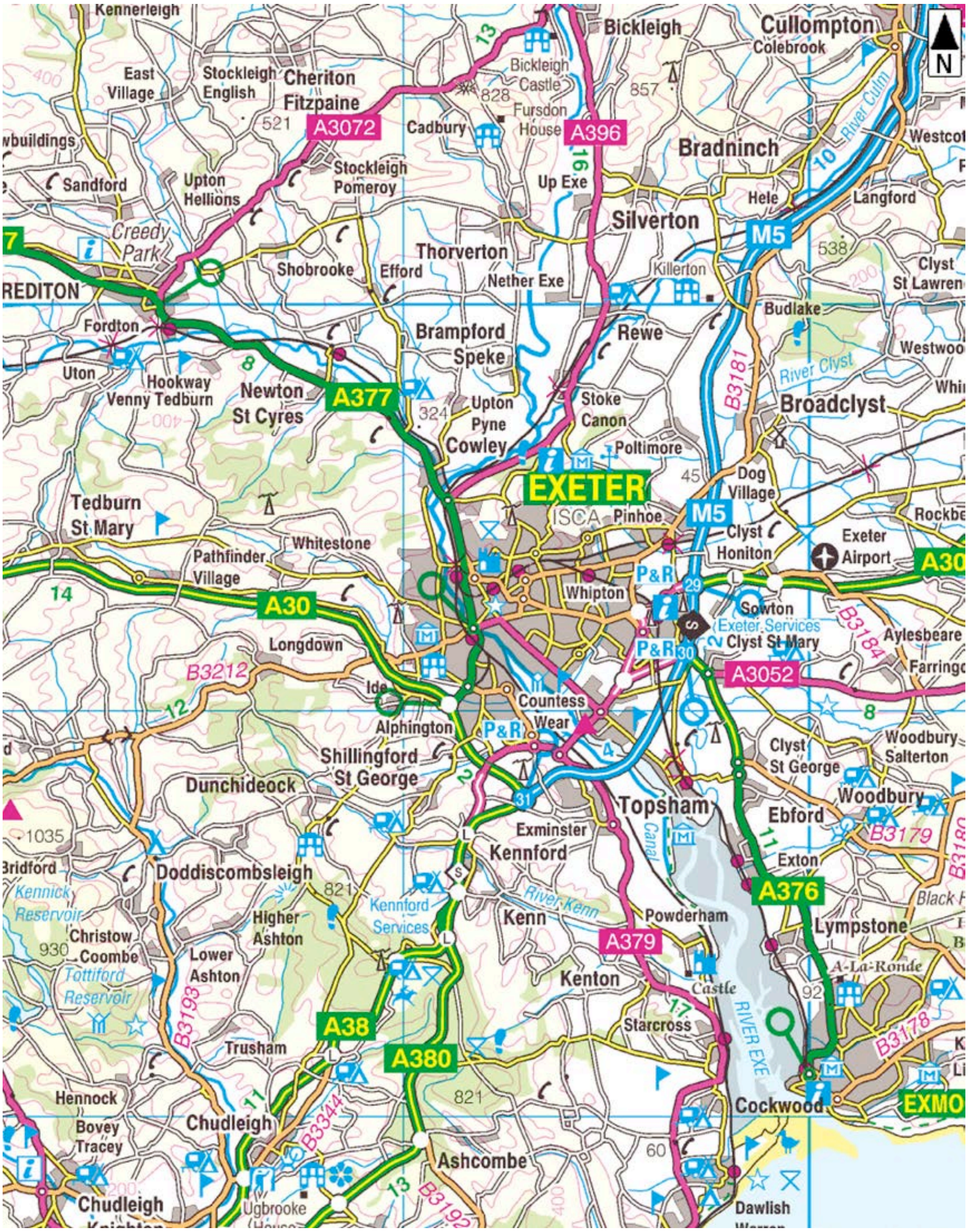


Figure 1: Map to show the location of the Law Library, 8-9, and 9a, The Close (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationary Office, © Crown Copyright)

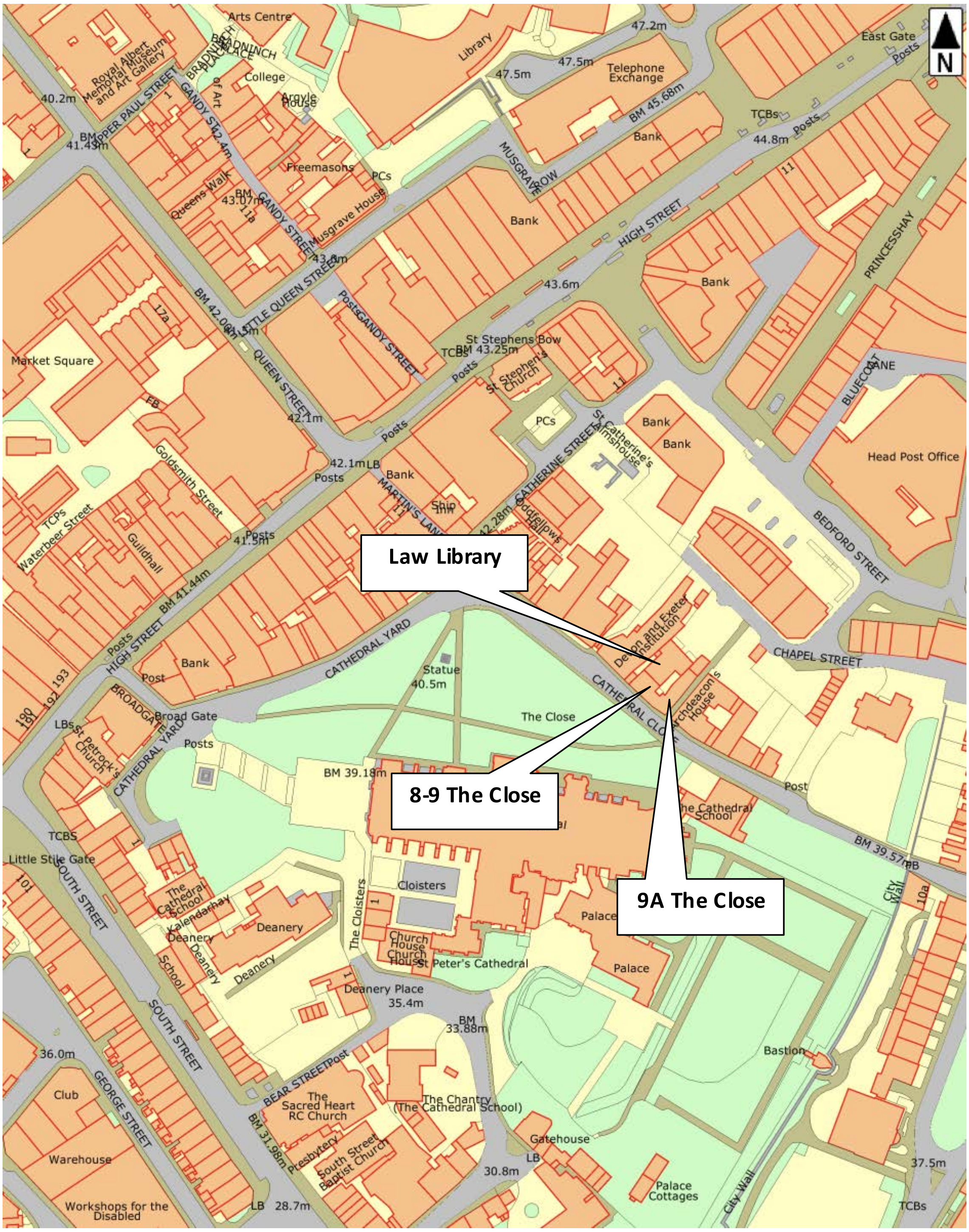


Figure 2: Map to show the location of the Law Library, 8-9, and 9a, The Close (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

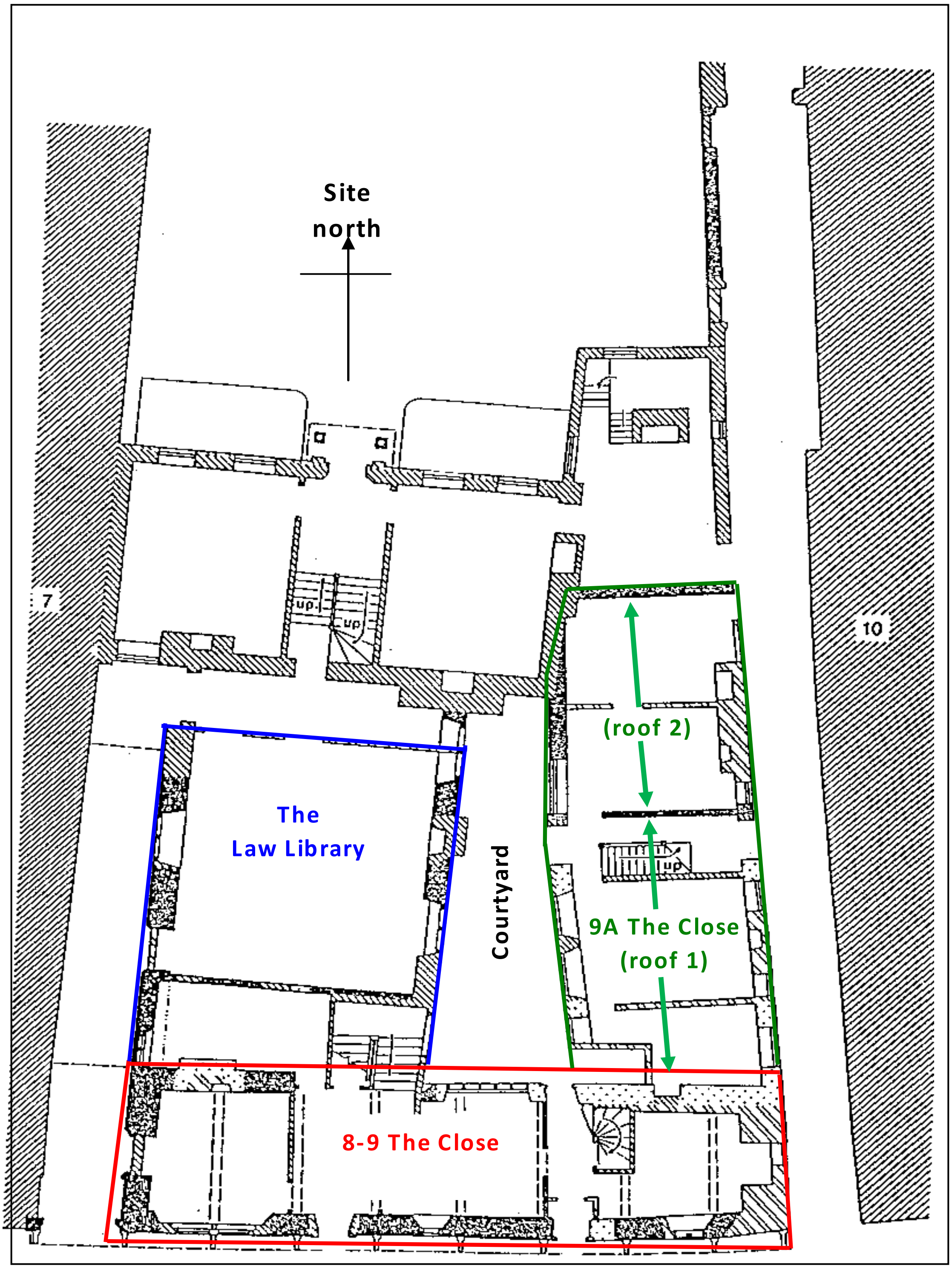


Figure 3: General plan to show layout of 8-9 The Close, 9a The Close, and the Law Library (Exeter Archaeology)

Figure 4: View of the small enclosed rear courtyard area from the attic of 9a The Close. To the right may be seen the southern end of the Law Library attached to the rear of numbers 8-9 The Close. Exeter Cathedral may be glimpsed beyond

Figure 5: 8-9 The Close; view of the passageway with its decorated arch at the west end of the front range

Figure 6a (top): View of Law Library roof

Figure 6b (bottom): View of a boss hiding the junction of timbers

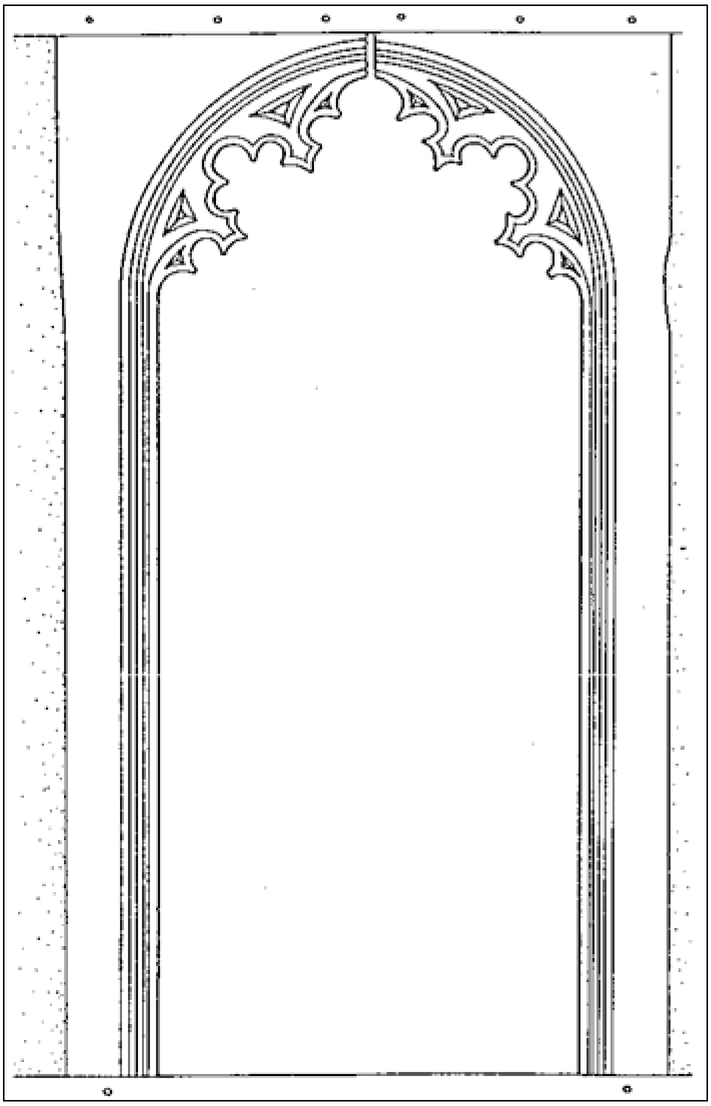


Figure 7: Drawing of the doorway (now blocked) between the open hall of the Law Library (rear west range) and 8-9 The Close (the front range) (after John Thorp)

Figure 8: View of the panels from 8-9 The Close

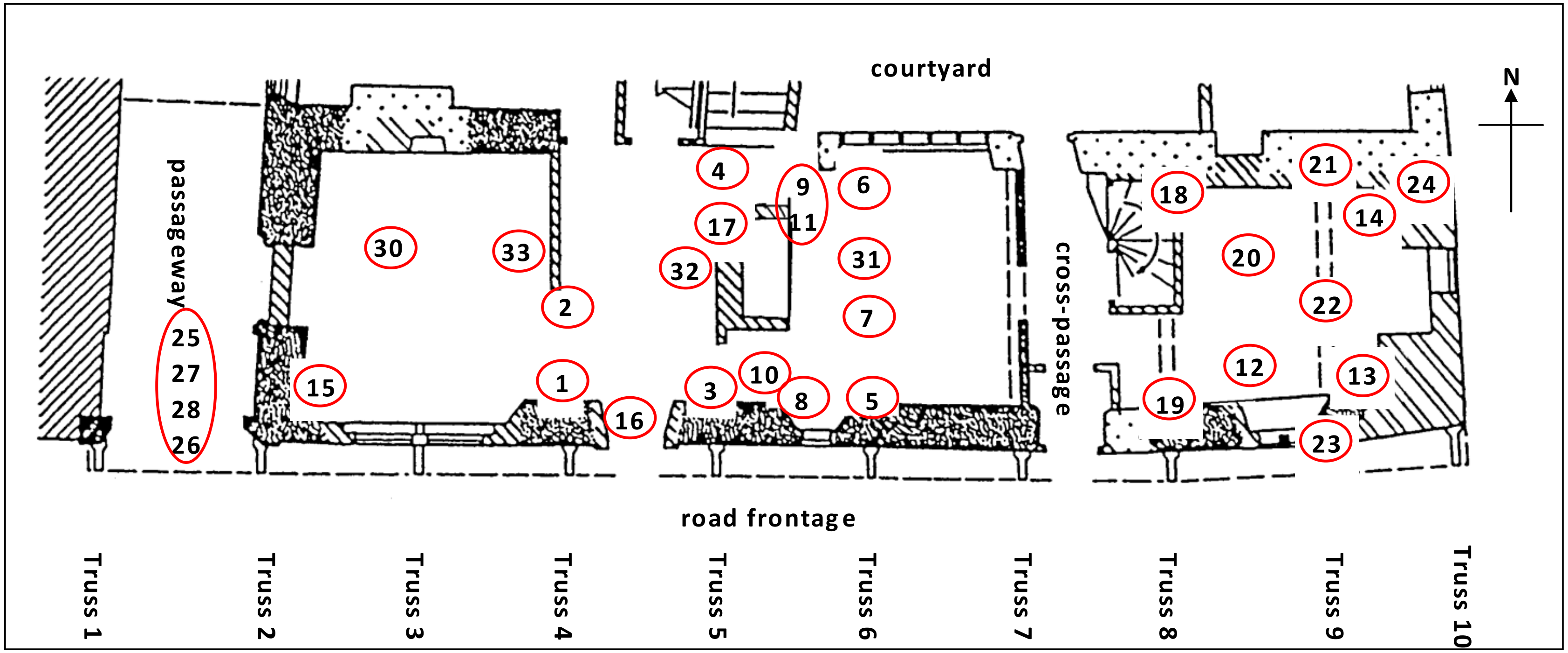


Figure 9a: 8-9 The Close; plan to show approximate position of sampled timbers (after Richard Parker, Exeter Archaeology)

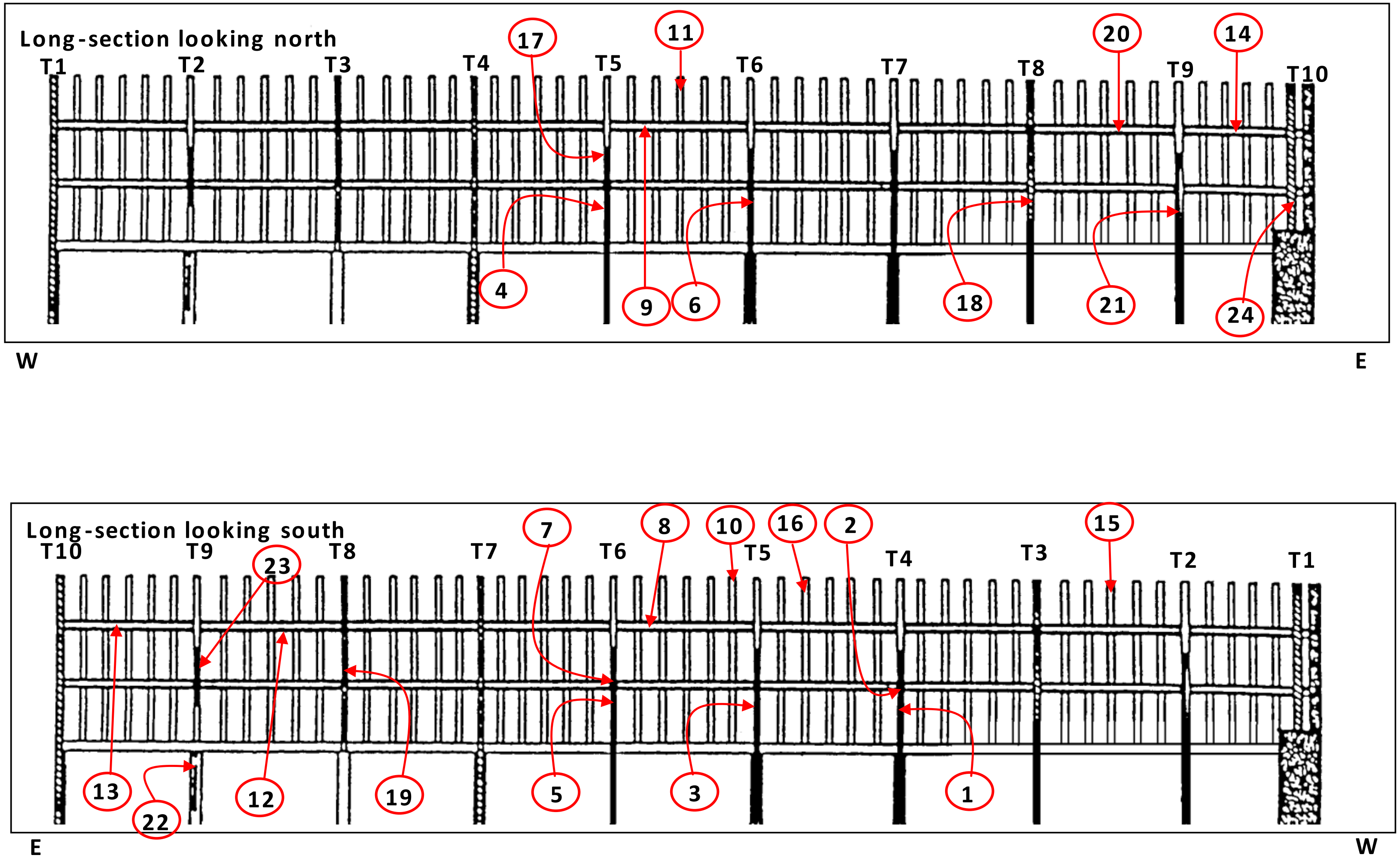
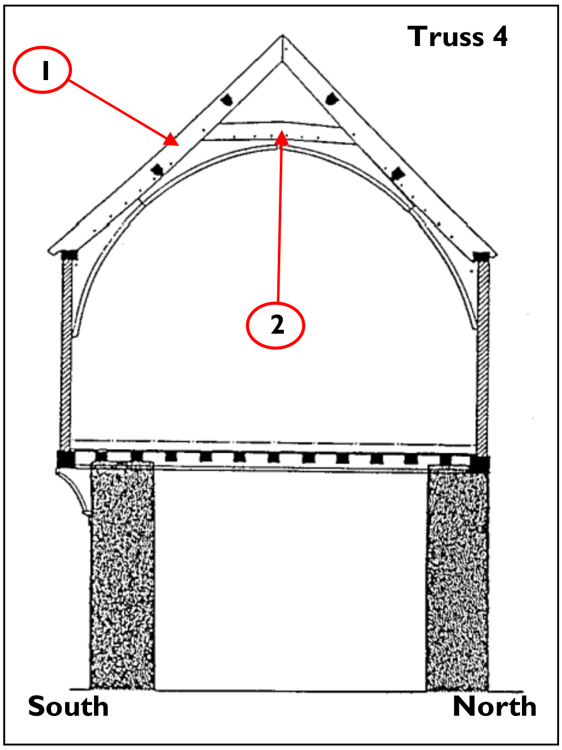


Figure 9b: 8-9 The Close (front range); long-sections to show sample locations (after Richard Parker, Exeter Archaeology)



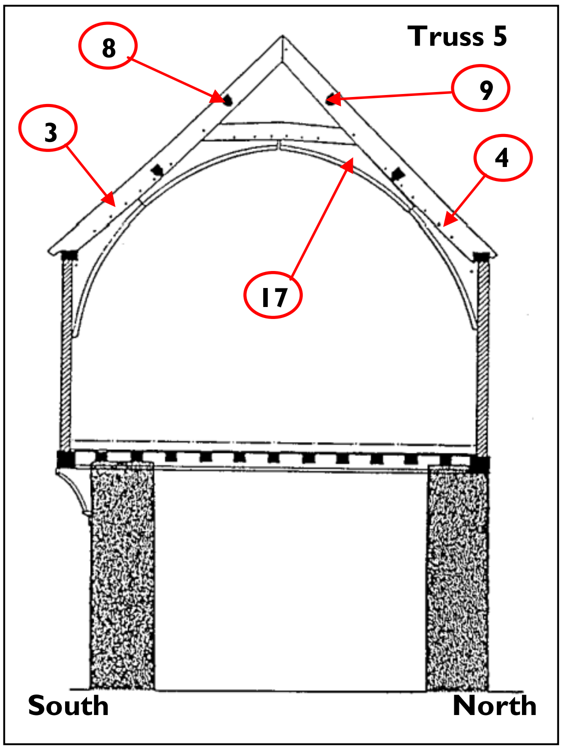


Figure 9c: 8-9 The Close (front range); cross-sections at trusses 4 and 5 to show sample locations (viewed from the east looking west) (after Richard Parker, Exeter Archaeology)

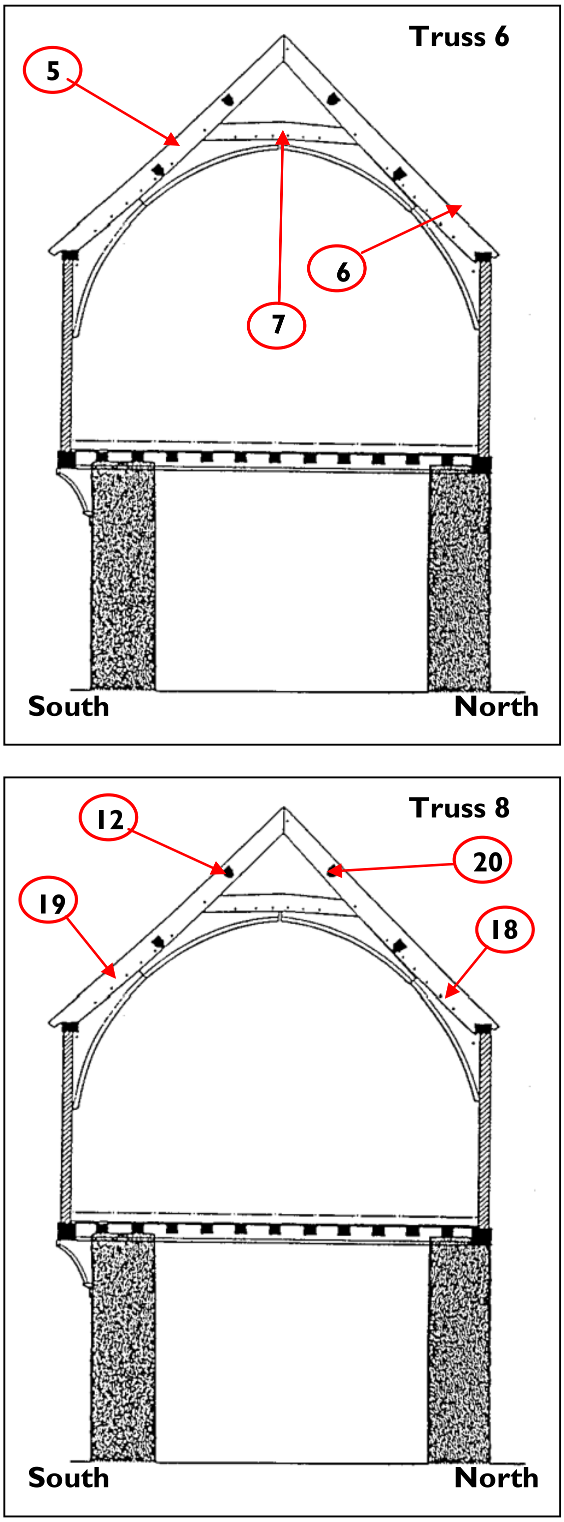


Figure 9d: 8-9 The Close (front range); cross-sections at trusses 6 and 8 to show sample locations (viewed from the east looking west) (after Richard Parker, Exeter Archaeology)

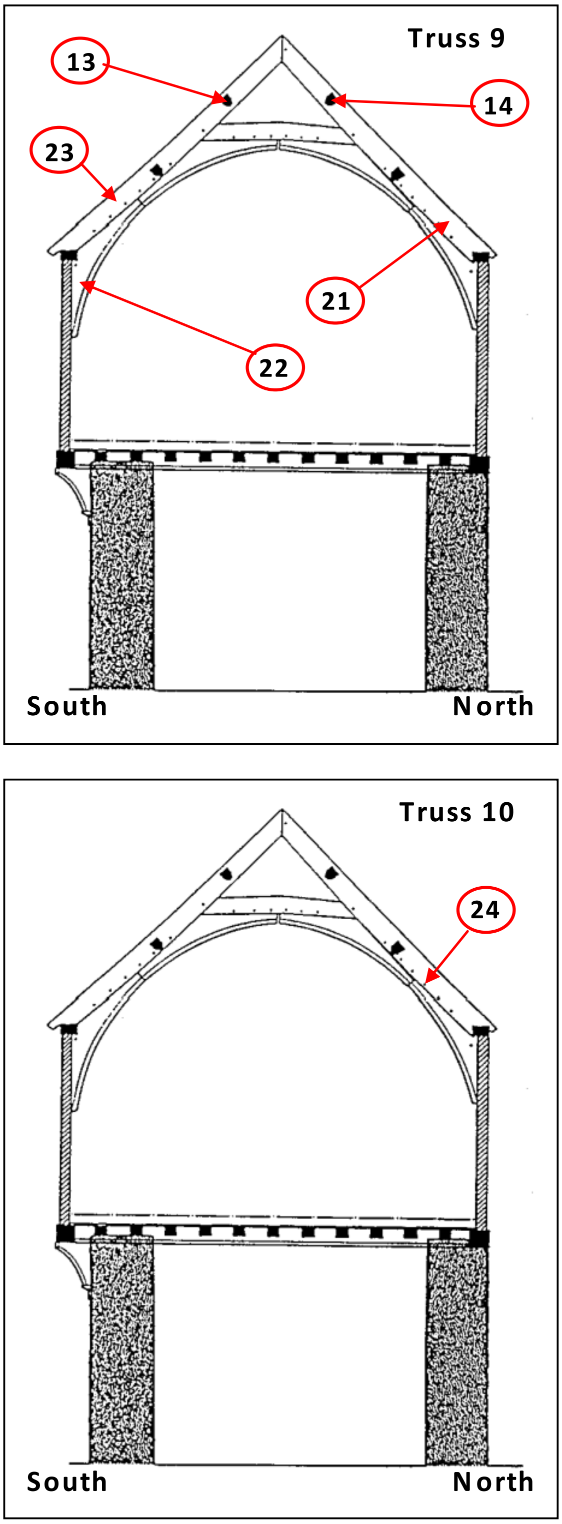


Figure 9e: 8-9 The Close (front range); cross-sections at trusses 9 and 10 to show sample locations (viewed from the east looking west) (after Richard Parker, Exeter Archaeology)

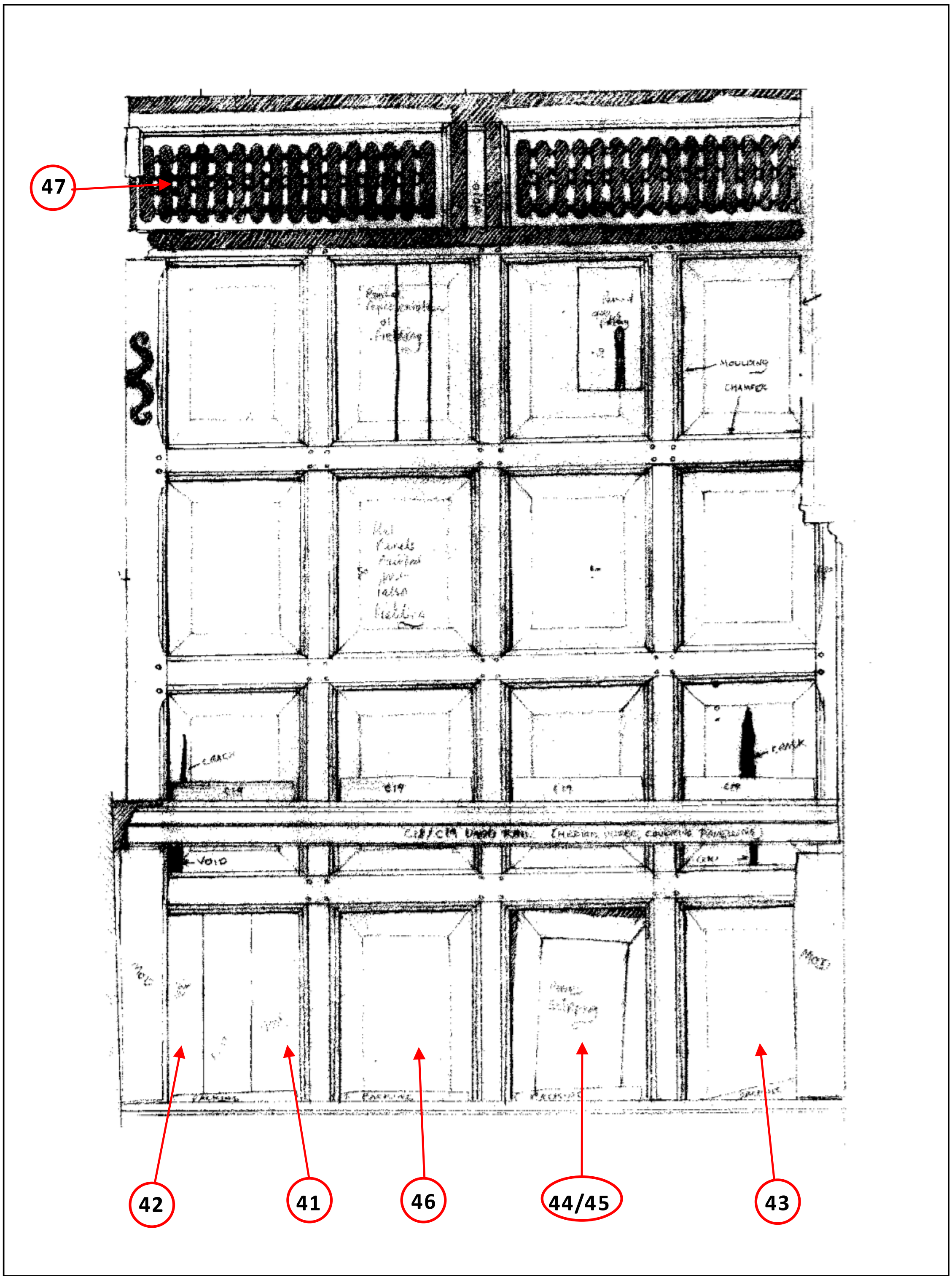


Figure 9f: Drawing of the panels from 8-9 The Close to show sample locations (after Richard Parker, Exeter Archaeology)

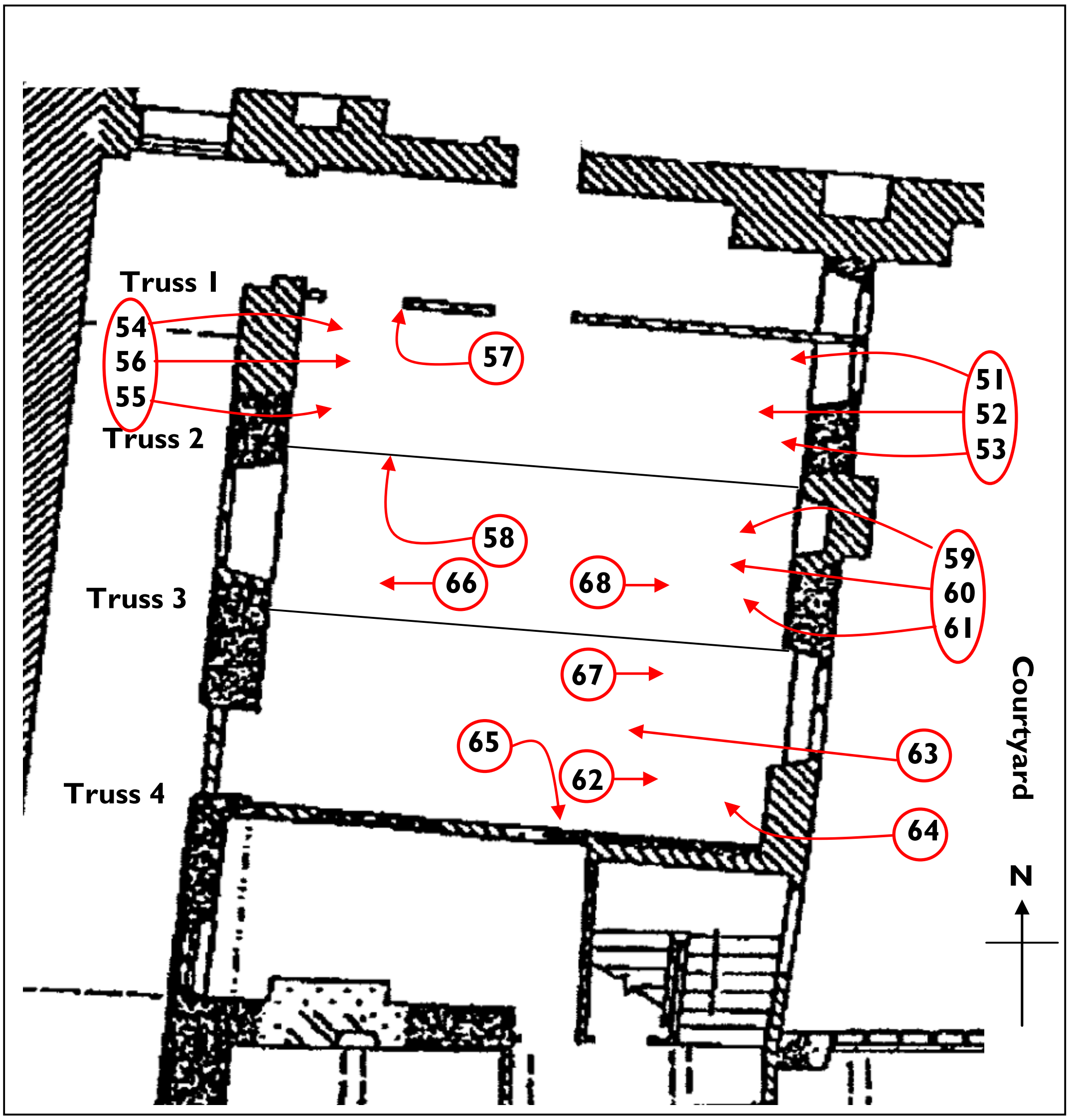


Figure 10a: Law Library (rear west range); plan to show approximate position of sampled timbers (after Richard Parker, Exeter Archaeology)

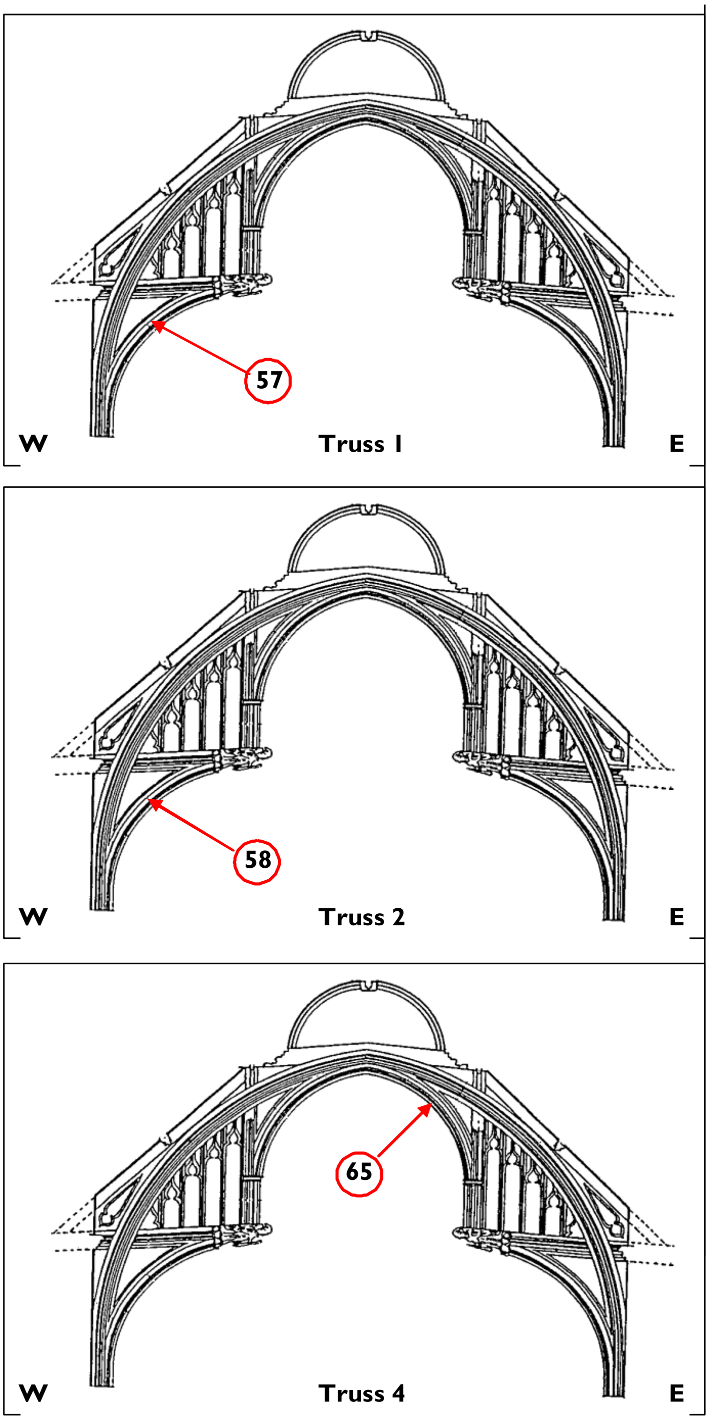


Figure 10b: Law Library (rear west range); drawing of the trusses to show sample locations (viewed from the south looking north) (after Ministry of Works, Ancient Monument Branch)

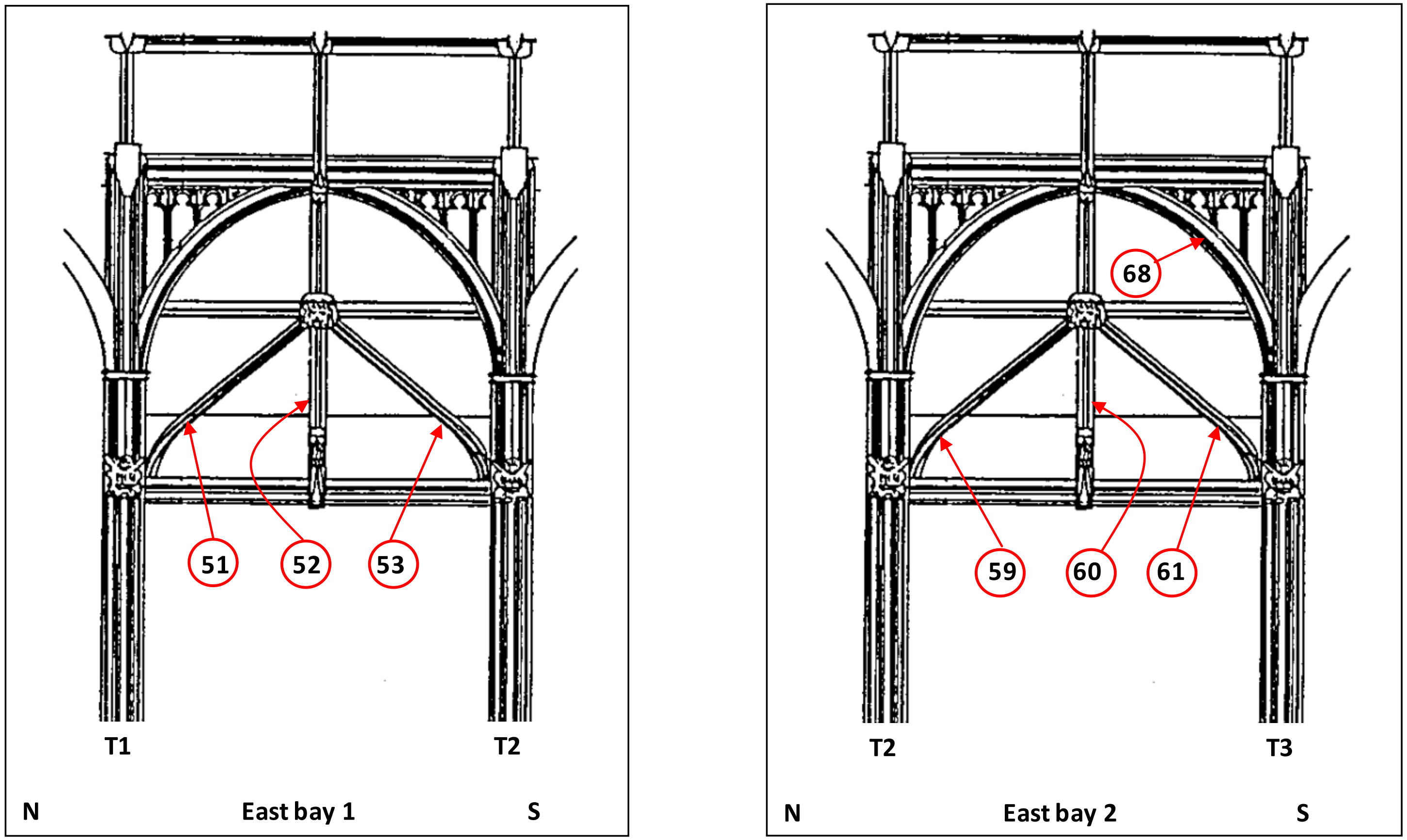


Figure 10c: Law Library (rear west range); drawing of east bays 1 and 2 to show sample locations (after Ministry of Works, Ancient Monument Branch)

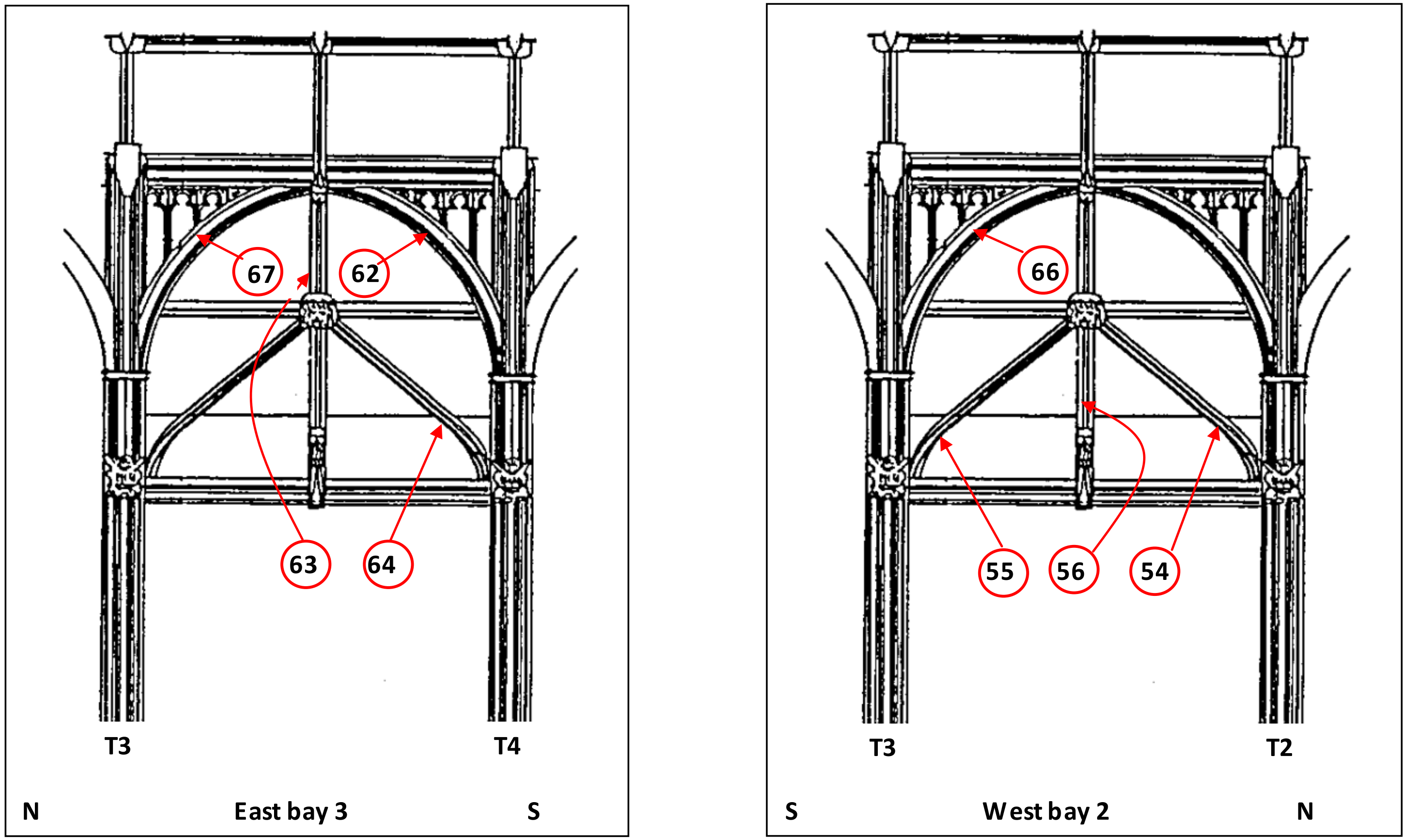


Figure 10d: Law Library (rear west range); drawing of east bay 3 and west bay 2 to show sample locations (after Ministry of Works, Ancient Monument Branch)

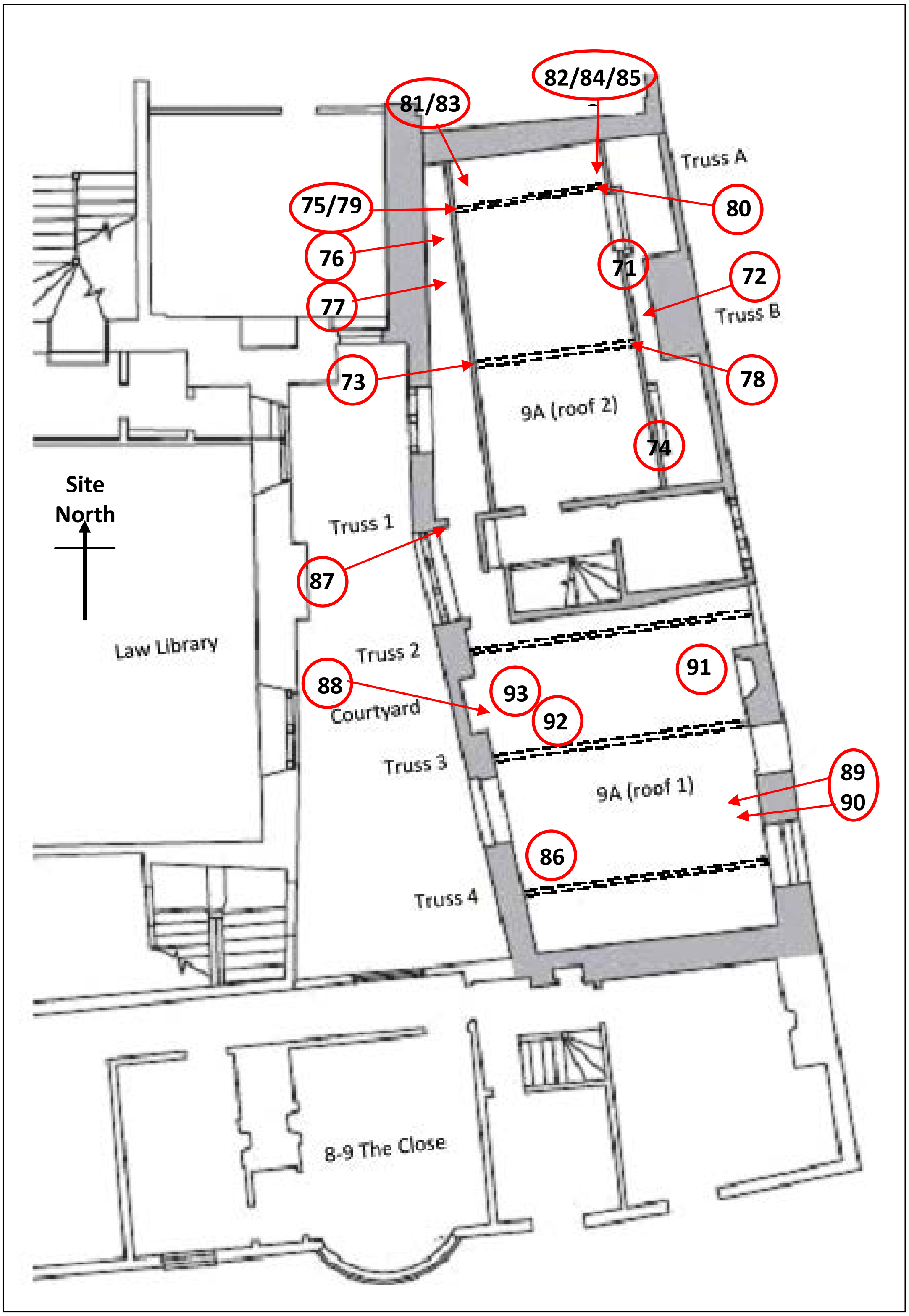


Figure 11a: 9a The Close; plan to show approximate position of sampled timbers (after Richard Parker, Exeter Archaeology)

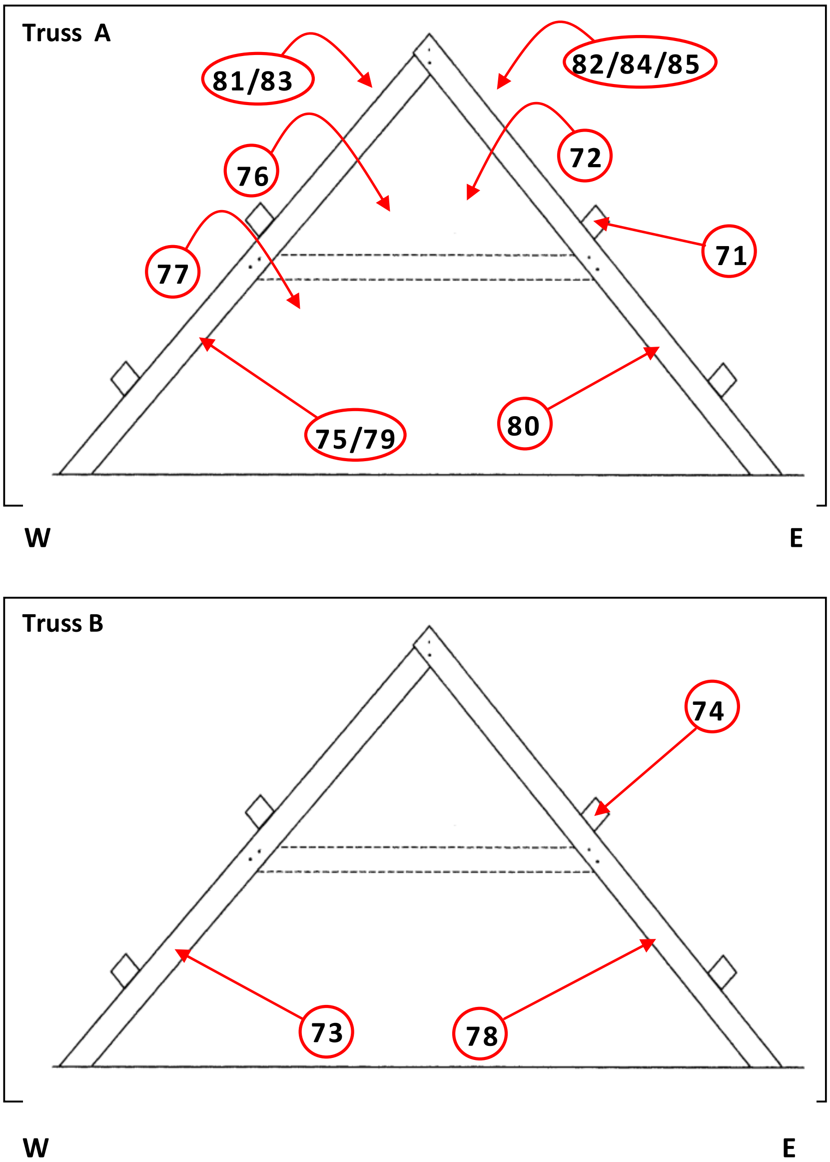


Figure 11b: 9a The Close (roof 2); trusses A and B showing sample locations (viewed from the south looking north)

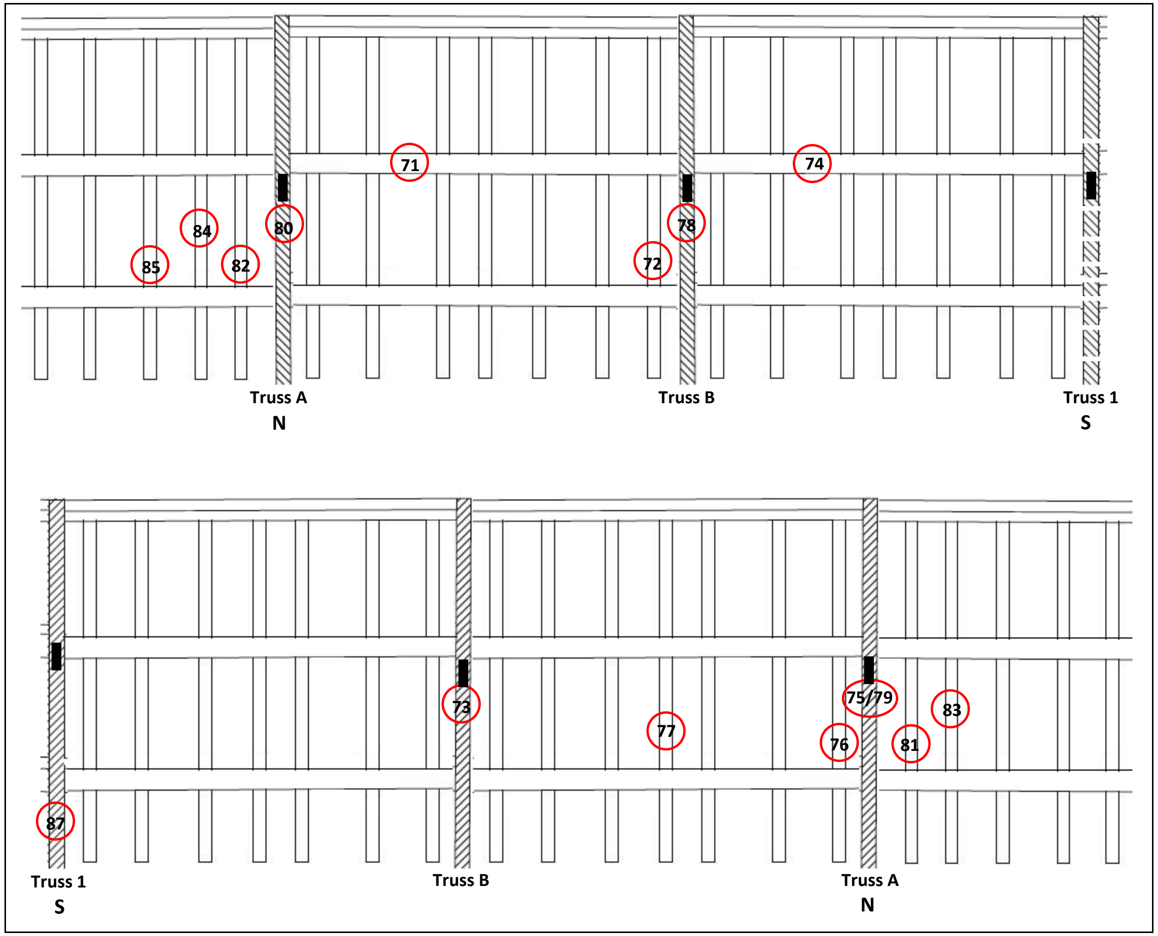


Figure 11c: 9a The Close (roof 2); long-sections through trusses A-B to show sample locations (after John Allan, Exeter Archaeology)

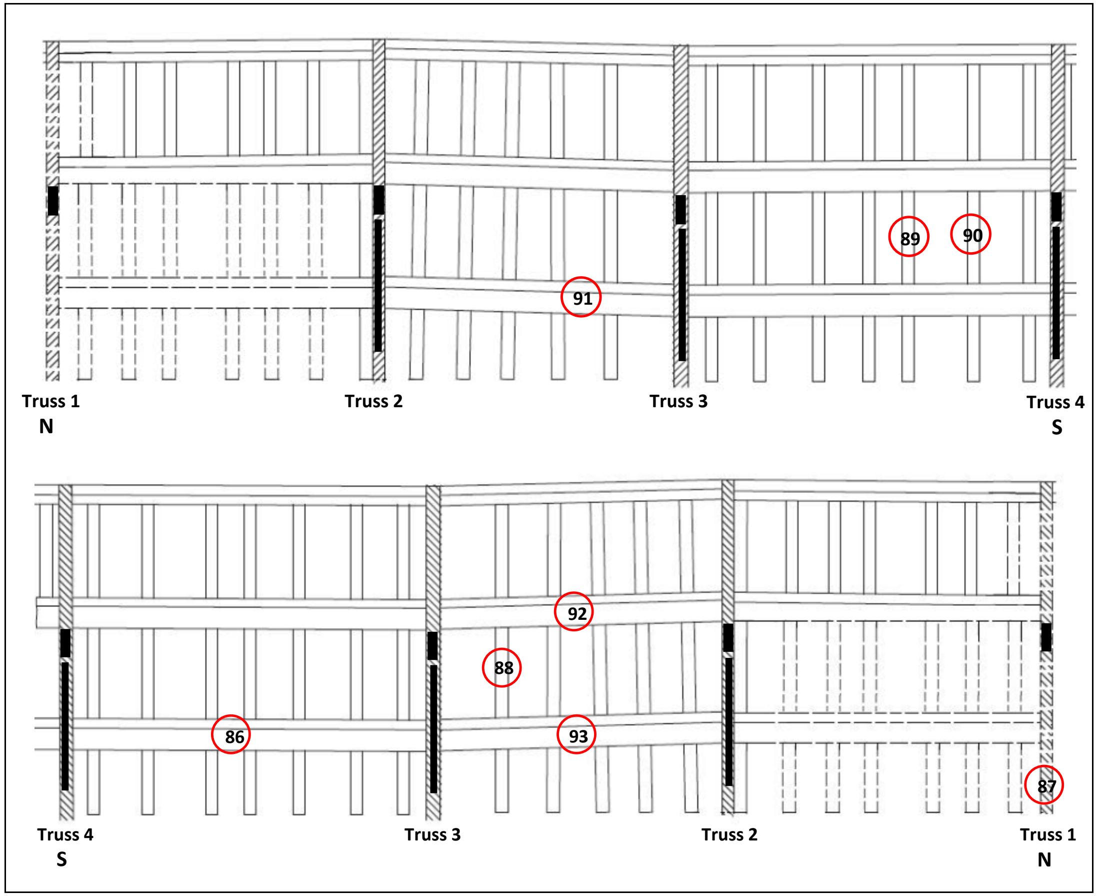


Figure 11d: 9a The Close (roof 1); long-sections through upper parts of trusses 1-4 showing sample locations (after John Allan, Exeter Archaeology)

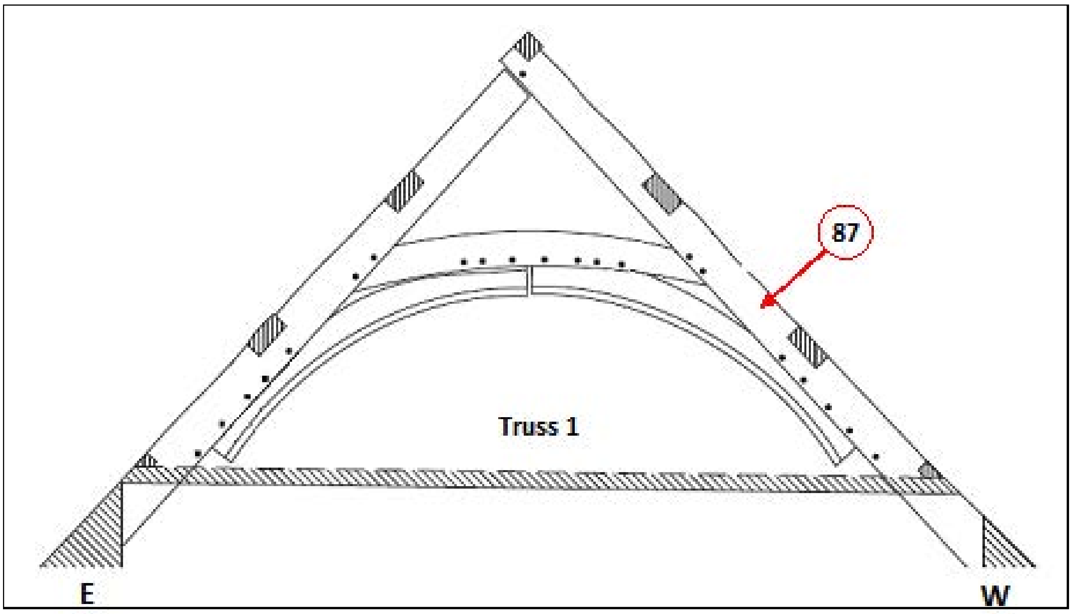
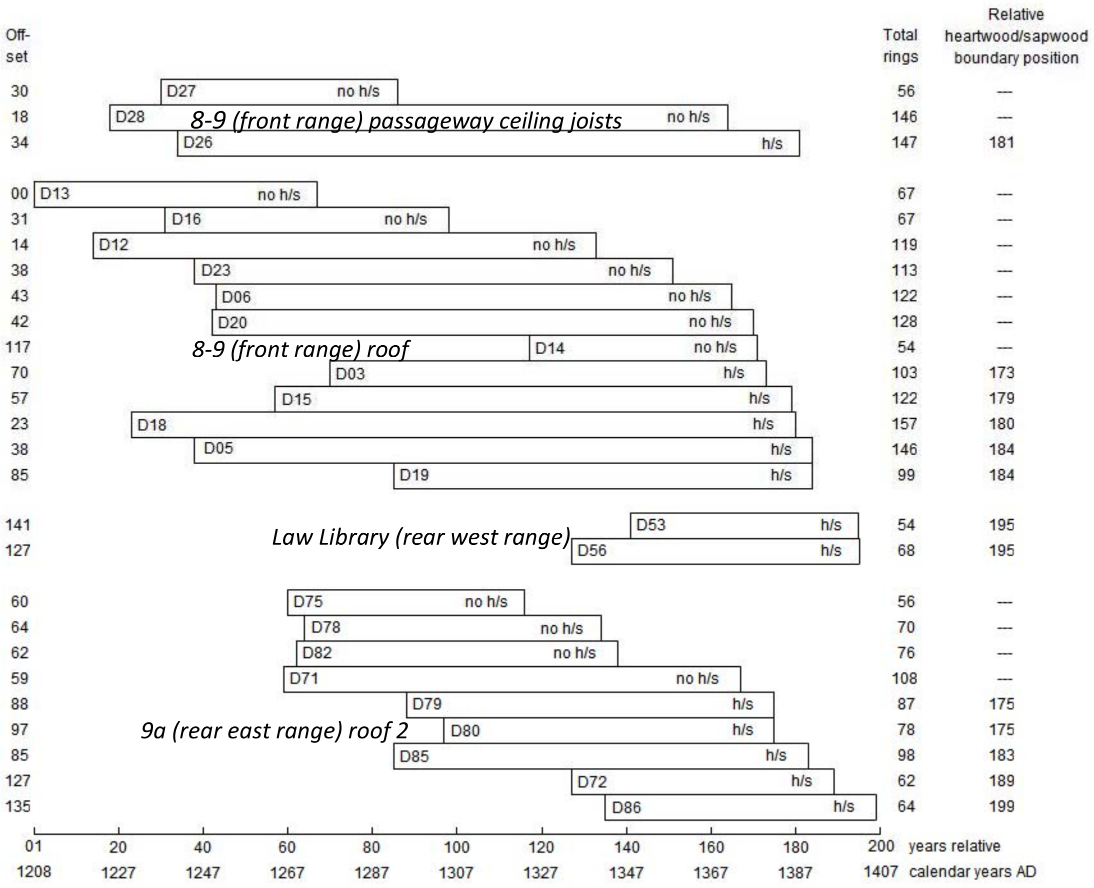


Figure 11e: 9a The Close (roof 1); cross-section at truss 1 showing sample location (viewed from the north looking south) (after John Allan, Exeter Archaeology)



Empty bars ☐ = heartwood rings

h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing. NB: Samples D75 & D79 are from the same timber)

Figure 12: Bar diagram of the samples in site chronology EXTDSQ01 sorted by sample location in last measured ring date order

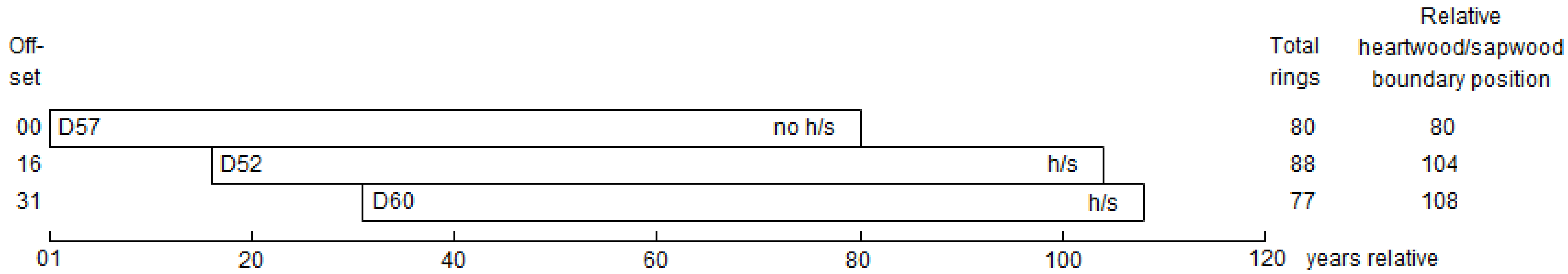
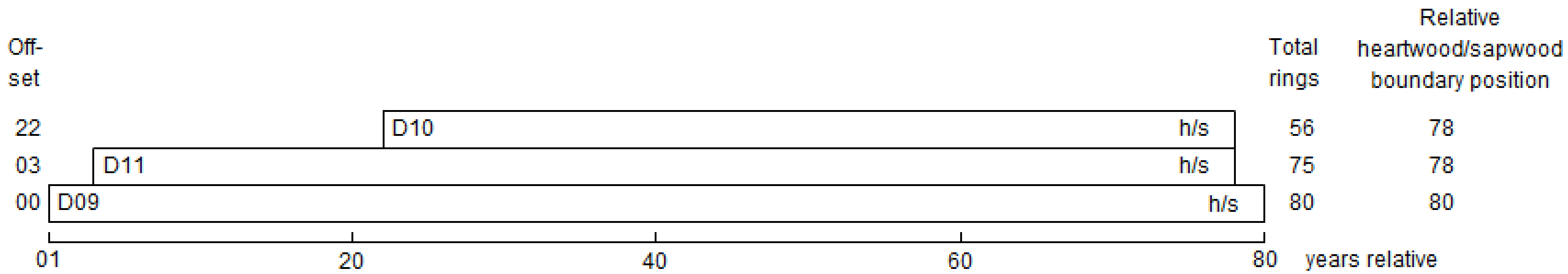


Figure 13: Bar diagram of the samples in site chronology EXTDSQ02



Empty bars [ ] = heartwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing

Figure 14: Bar diagram of the samples in site chronology EXTDSQ03

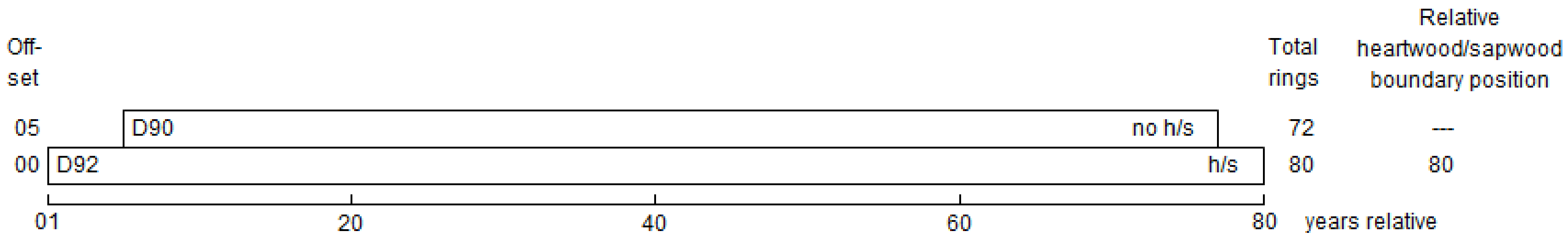
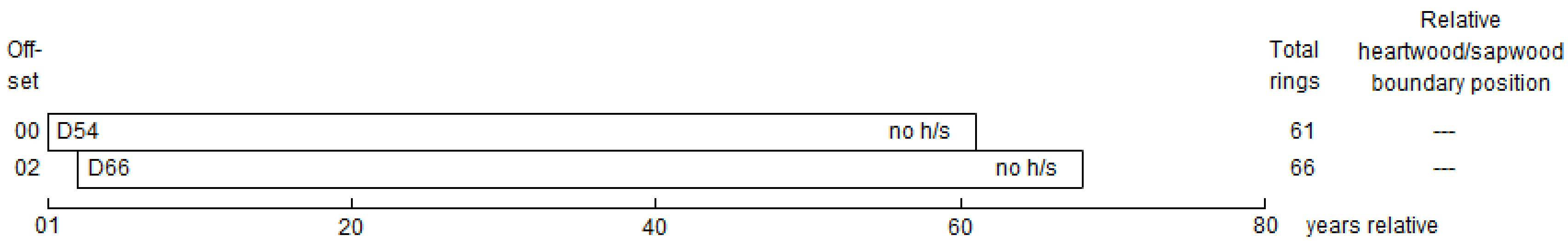


Figure 15: Bar diagram of the samples in site chronology EXTDSQ04



Empty bars = heartwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing

Figure 16: Bar diagram of the samples in site chronology EXTDSQ05

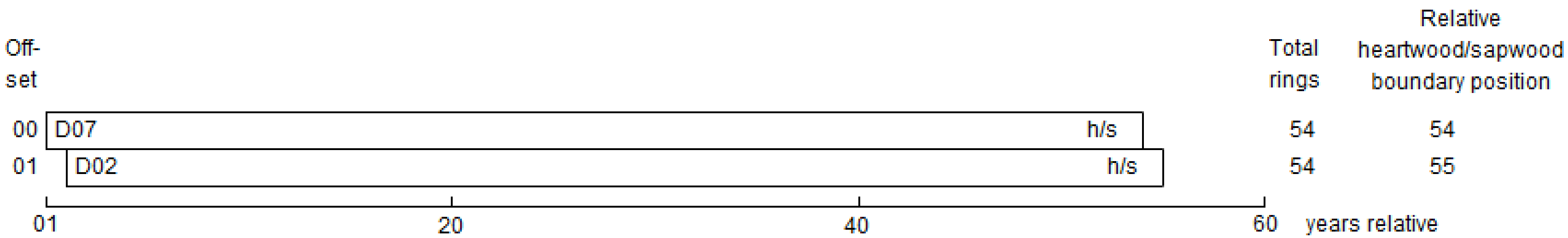
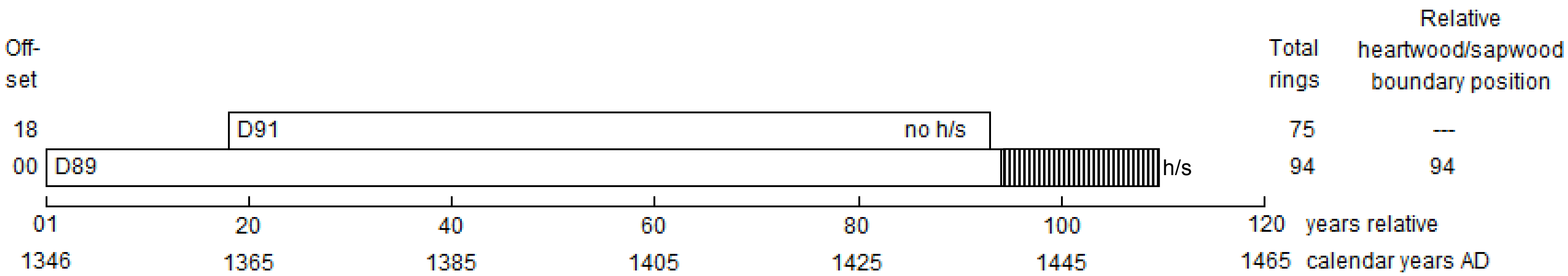


Figure 17: Bar diagram of the samples in site chronology EXTDSQ06



Empty bars = heartwood rings, shaded area = unmeasured heartwood rings

h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing

Figure 18: Bar diagram of the samples in site chronology EXTDSQ07

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

EXT-D01A 54
274 323 386 346 228 298 366 354 383 286 282 287 266 122 130 160 269 277 324 268
181 130 130 139 224 293 156 74 109 122 145 82 93 42 47 74 112 223 144 180
207 271 263 343 411 218 157 182 190 228 283 262 321 439
EXT-D01B 54
238 343 388 343 268 281 367 351 363 318 305 315 245 123 138 152 285 343 335 241
164 164 126 150 244 307 149 68 124 116 133 77 107 43 39 83 109 229 138 169
230 274 272 329 421 223 171 199 202 194 274 258 336 402
EXT-D02A 54
251 218 232 171 105 106 143 219 369 264 305 252 183 153 210 290 220 191 188 195
148 178 207 168 158 292 306 258 204 152 260 165 229 193 236 242 165 193 231 249
286 219 321 277 233 192 185 221 296 205 159 200 213 289
EXT-D02B 54
303 216 212 178 116 107 144 246 358 276 301 218 201 166 199 276 229 203 190 189
155 168 208 185 157 287 284 262 176 163 240 165 239 198 270 229 170 230 236 212
303 228 316 273 237 202 219 174 153 197 181 188 226 314
EXT-D03A 103
33 44 48 51 54 75 53 50 68 55 63 63 83 67 112 104 136 158 180 170
152 112 81 78 96 85 65 46 67 62 83 63 46 67 84 94 85 97 113 115
136 108 94 123 122 72 109 82 82 80 49 54 54 57 71 71 47 60 74 68
78 85 90 67 74 45 44 74 82 81 101 129 101 105 70 77 74 42 47 82
50 66 73 78 44 93 67 72 63 69 68 89 81 82 74 89 137 122 81 70
60 69 88
EXT-D03B 103
38 36 50 49 51 73 61 46 67 53 62 70 87 57 109 108 135 153 176 167
155 113 79 71 103 86 58 54 64 58 98 65 43 69 100 80 87 106 104 120
144 108 101 117 126 97 99 96 77 74 47 51 60 58 71 58 49 69 67 65
73 106 81 65 66 54 46 72 91 82 104 124 97 94 77 83 68 37 59 73
49 70 67 73 56 90 73 72 70 71 68 93 75 84 59 101 117 122 88 66
60 73 89
EXT-D04A 99
160 68 74 88 67 116 105 84 69 84 88 144 105 112 131 138 117 92 77 77
100 120 96 103 92 80 104 152 134 191 198 164 196 226 271 230 224 238 271 255
329 293 120 65 48 66 74 67 106 84 84 102 139 112 118 82 57 44 77 79
98 102 98 111 133 115 143 128 130 145 155 138 127 150 125 97 103 115 126 141
127 127 127 160 173 190 163 171 150 152 90 98 110 105 122 107 178 148 172
EXT-D04B 99
146 65 69 82 65 114 95 87 70 76 88 135 118 95 122 131 120 93 81 75
112 99 109 87 91 89 108 156 137 187 191 168 206 219 310 226 234 256 269 263
317 285 135 77 53 64 76 59 109 65 96 120 122 116 120 68 58 52 79 76
98 100 98 110 131 115 140 128 120 165 159 141 124 151 120 99 98 123 131 127
138 120 146 157 184 195 153 169 157 132 96 99 110 121 121 111 170 148 165
EXT-D05A 146
83 130 114 202 133 102 96 84 43 44 26 31 48 67 119 134 146 88 49 82
151 156 211 206 168 255 232 275 165 78 82 82 51 90 114 137 100 109 72 89
126 74 86 114 99 97 127 75 73 62 93 74 71 41 26 37 70 80 42 42
38 51 44 63 68 41 44 53 64 60 81 98 117 141 154 140 158 109 108 76

97 87 98 96 86 44 29 23 32 35 34 47 33 37 36 35 34 37 26 43
48 43 83 71 65 78 69 103 90 49 90 136 87 153 171 254 259 187 180 169
239 377 410 293 233 255 217 279 225 157 148 125 168 151 109 106 109 224 226 219
253 152 193 151 109 137
EXT-D05B 146
84 120 127 198 133 106 115 78 46 35 25 41 47 61 129 131 142 101 59 85
162 161 225 212 164 252 214 227 163 94 68 79 60 81 113 144 121 116 68 87
114 70 85 99 126 96 132 71 63 64 90 87 69 40 25 38 65 79 45 49
39 41 52 63 71 59 37 52 76 51 73 106 117 142 149 130 158 133 104 86
91 93 101 98 79 51 21 28 31 36 39 43 33 37 36 29 40 33 32 42
40 53 83 84 56 75 66 112 89 49 88 128 96 137 183 261 239 183 173 187
251 364 417 281 226 264 216 262 243 174 150 139 174 157 96 104 106 216 217 221
251 153 194 126 120 171
EXT-D06A 122
147 64 67 87 105 68 80 108 96 90 122 127 87 33 31 58 73 98 94 103
87 96 119 145 73 87 104 75 78 96 89 106 80 74 75 113 82 92 98 103
112 176 226 211 158 220 197 212 161 146 134 130 114 69 52 40 51 60 48 92
128 172 155 190 144 181 182 163 166 165 207 236 170 157 164 108 105 132 130 119
118 122 138 141 141 124 150 132 128 157 140 120 112 128 146 146 164 151 196 160
249 139 143 178 152 148 174 192 203 175 142 103 167 170 134 186 169 156 230 177
127 190
EXT-D06B 122
162 68 68 95 99 60 92 104 85 97 117 118 91 34 29 53 73 95 101 93
89 106 121 134 105 90 98 84 90 107 109 98 79 75 78 119 83 80 116 97
122 174 247 206 169 234 179 214 155 143 125 136 106 65 57 39 44 60 56 93
123 165 140 185 148 191 195 196 139 163 207 238 178 179 164 121 108 135 126 129
120 138 161 133 134 122 153 109 121 142 144 122 114 126 142 138 164 150 201 157
235 140 145 180 144 148 173 184 218 139 162 110 154 176 127 208 172 160 237 163
144 192
EXT-D07A 54
239 230 206 163 210 178 165 158 194 192 218 236 183 136 110 149 163 115 120 145
211 225 218 417 307 318 459 370 353 208 151 174 115 211 121 169 218 103 138 141
171 193 147 186 244 211 196 246 95 220 116 96 110 144
EXT-D07B 54
223 239 199 198 213 184 147 163 185 216 169 216 190 174 122 136 209 122 114 149
204 247 241 414 324 314 422 398 363 201 135 189 101 223 127 155 238 120 130 134
195 219 165 184 231 212 150 210 139 223 146 124 85 178
EXT-D08A 54
222 249 290 349 281 229 292 282 273 199 279 240 212 390 184 338 234 265 266 209
294 318 413 432 340 258 286 359 394 305 342 349 346 321 244 356 343 329 268 385
217 250 254 229 362 202 351 208 272 273 206 247 268 259
EXT-D08B 54
284 261 276 367 276 169 299 268 266 199 268 253 214 362 241 330 264 248 270 205
340 327 392 433 333 248 291 411 399 280 334 353 328 294 243 342 360 321 270 382
189 242 265 247 349 221 332 207 286 292 202 278 258 281
EXT-D09A 80
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EXT-D80B 78

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126 119 133 140 133 204 98 128 196 273 256 174 162 131 106 220
EXT-D83A 54
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345 329 395 303 335 276 313 325 340 216 222 343 207 278 135
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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 A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

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

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

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

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

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

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

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

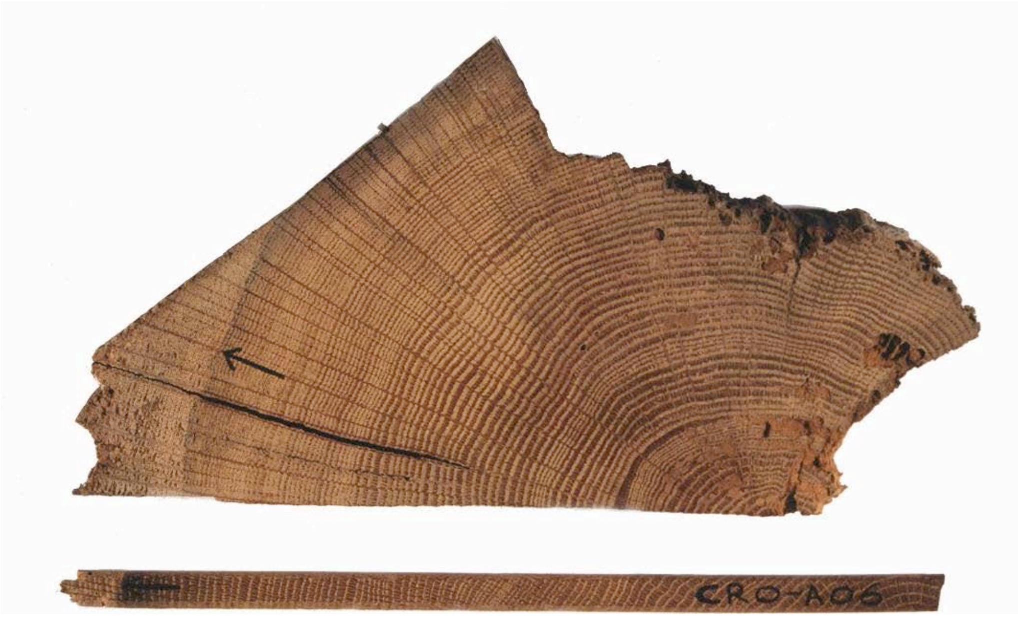


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

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

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

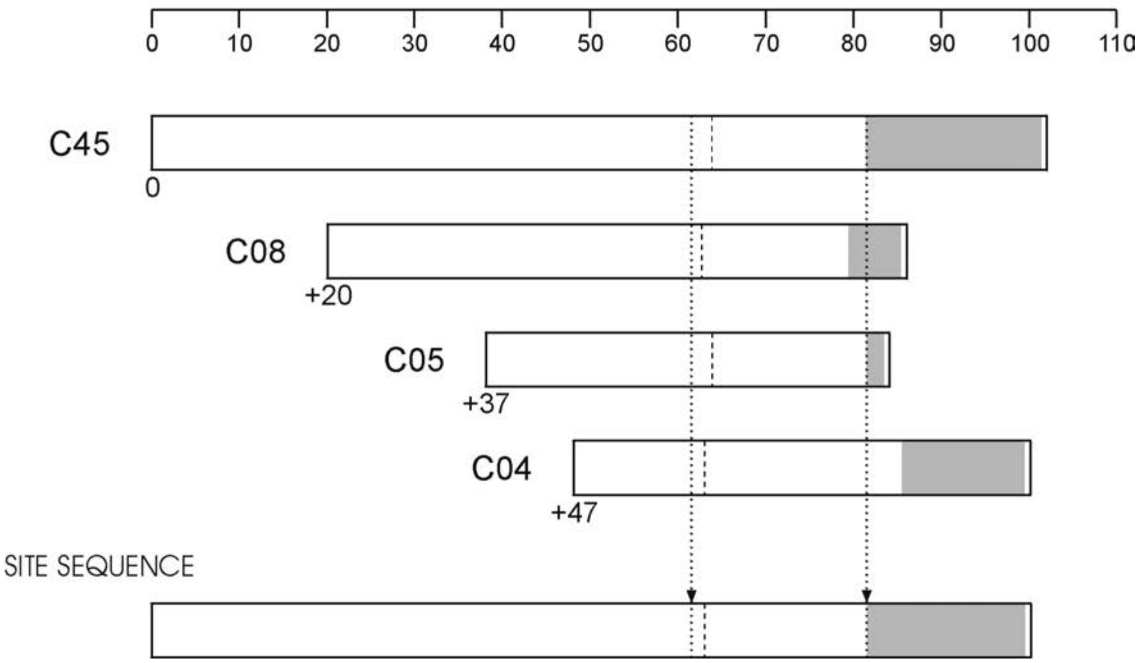


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

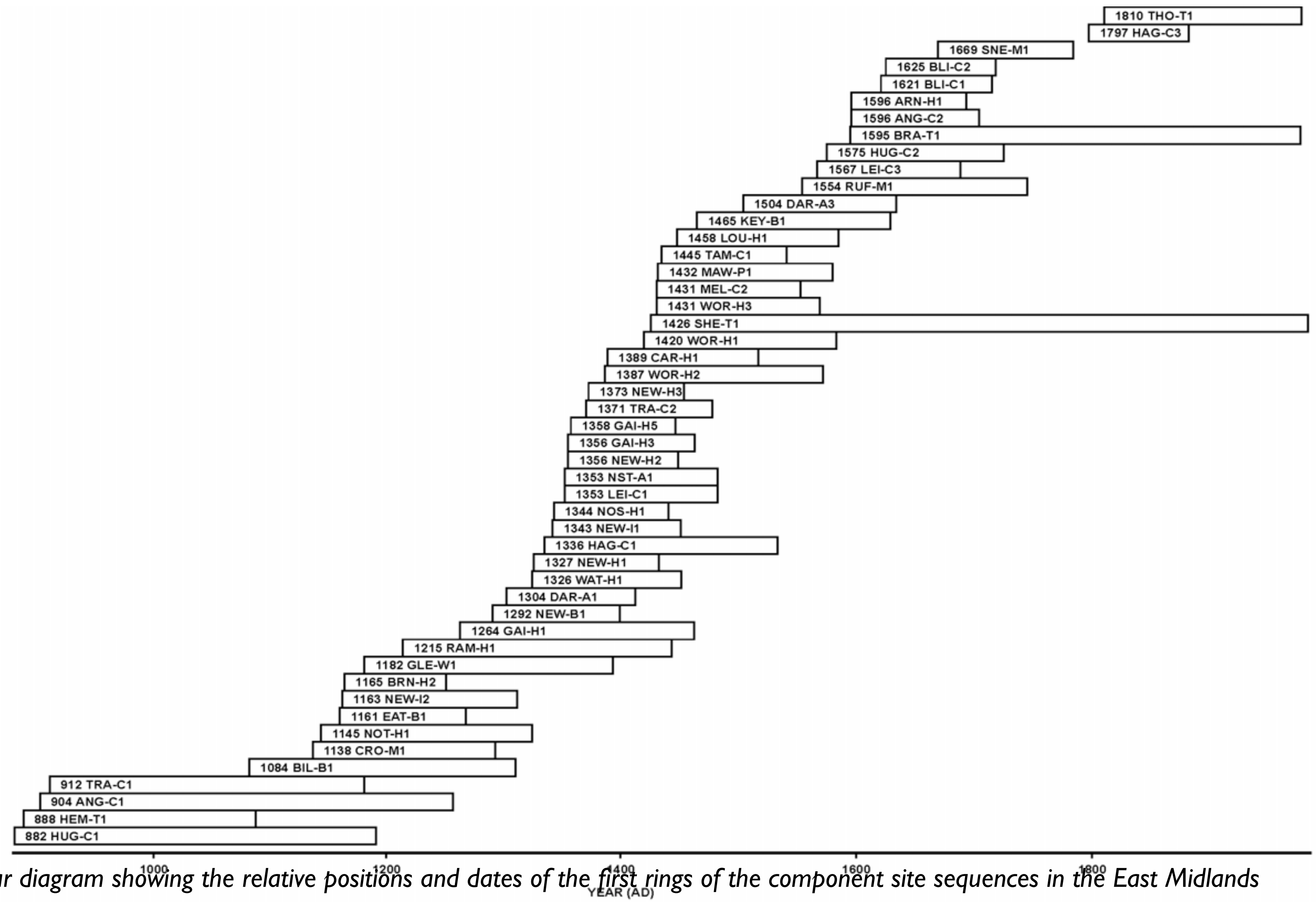
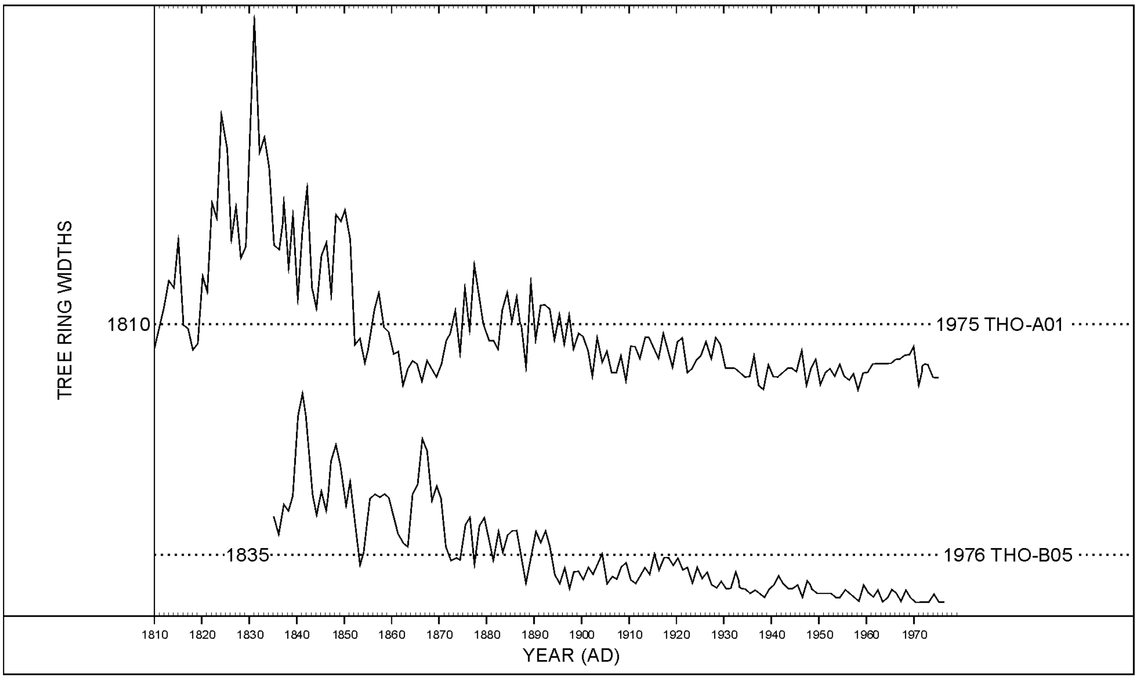


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

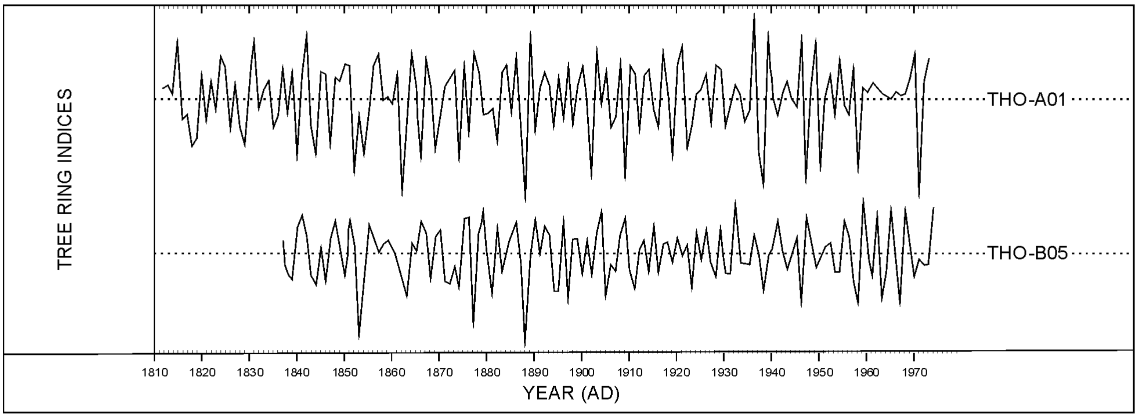


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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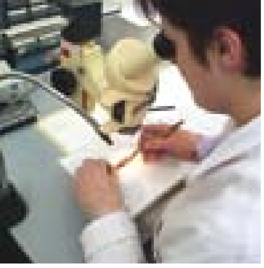
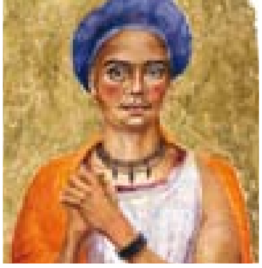



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