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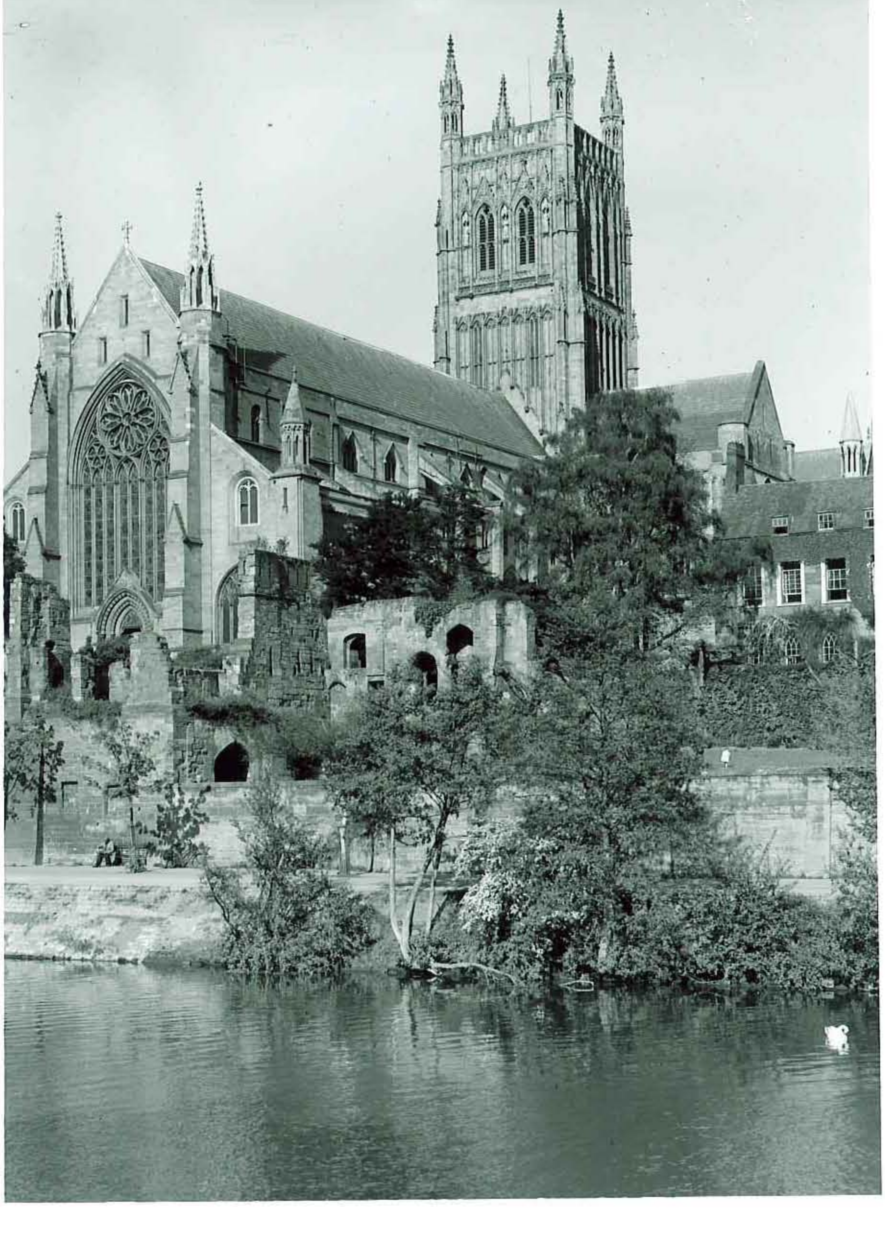

Frontispiece: Worcester Cathedral from the south-west, across the river Avon. (© Crown copyright. NMR.)

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Tree-Ring Analysis of Timbers from the Roof of St John Chapel, and the Connecting Roof, Worcester Cathedral, Worcester

R E Howard[1], Dr R R Laxton[2] & Dr C D Litton[2]

Summary

A total of forty-three samples from the roofs of St John Chapel and the connecting roofs of Worcester Cathedral were analysed by tree-ring dating. This analysis produced five site chronologies.

This first site chronology, WORCSQ07, consisting of twelve samples, has 80 rings and spans the period AD 1667 - AD 1746. Interpretation of the sapwood on these samples indicates that a number of timbers used in the Chapel roof were felled in AD 1743 with one timber being felled in AD 1746. The connecting roof contains one timber felled in AD 1743 and a number of others felled in AD 1746. This suggests that the last time that this roof was repaired was in AD 1746.

The second site chronology, WORCSQ08, has 131 rings spanning AD 1286 - AD 1416. The estimated felling dates on these timbers, used in both the St John Chapel and the connecting roofs, shows that they could have been felled in the early or mid-fifteenth century.

The third site chronology, WORCSQ09 has 128 rings spanning AD 1495 -AD 1622. It is made up of samples from St John Chapel only and suggest the timbers have a felling date in the range AD 1635 - 40.

The fourth site chronology, WORCSQ10, contains samples from three ex-situ beams found in the St John Chapel roof. The site chronology is 90 rings long spanning AD 1352 -AD 1441. The felling date of these timbers cannot be reliably estimated, but it is unlikely to be before AD 1456.

A fifth and final site chronology, WORCSQ11, is made up of oak boards covering the St John Chapel roof. This 63 ring sequence could not be cross-matched with any reference chronologies and the samples therefore remain undated.

This analysis shows that the roof of St John Chapel and the connecting roof contains much reused timber and that the last major repair phase was in the AD 1740s.

Keywords

Dendrochronology
Standing Building

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TREE-RING ANALYSIS OF TIMBERS FROM THE ROOF OF ST JOHN CHAPEL, AND THE CONNECTING ROOF, WORCESTER CATHEDRAL, WORCESTER

Introduction

Worcester Cathedral (frontispiece), standing in a prominent position on the east bank of the river Severn (SO 850545; Fig 1) has a long history. The bishopric was founded in the seventh century and the first Cathedral was dedicated to St Peter. Oswald, who was made bishop in AD 961, built a new cathedral, dedicated to St Mary. The presbytery of St Peter's was rebuilt following a Danish raid in AD 1041. Both early Cathedrals appear to have been demolished around the time St Wulfstan started the present Cathedral in AD 1084 (although the current hypothesis is that the Chapter House is a remodelling of a late Anglo-Saxon rotunda).

Surviving work of St Wulfstan's period includes the crypt, western transepts, cloisters, and Chapter House. In AD 1175 the crossing tower fell down and was rebuilt (Guy 1994). It was rebuilt again the AD 1370s. In AD 1224 the construction of a new east end was started under bishop William of Blois. Much of the existing decorated architecture at the east end belongs to this phase, with additional work in the perpendicular style dating from the late-fourteenth or early-fifteenth century. There was also a considerable amount of rebuilding activity in the nineteenth century

A modest amount of sampling for tree-ring analysis has been undertaken from timbers of the nave roof. This was commissioned by the Dean and Chapter of Worcester Cathedral in 1993, the work being funded by English Heritage (Howard *et al* 1995). The 1993 analysis indicated that, although a significant number of samples could not be dated, a certain amount of timber was felled in the early-seventeenth century, for repair work undertaken at that time. That programme of sampling showed that some earlier timbers were reused.

A much larger programme of sampling for tree-ring analysis, funded by English Heritage, has been undertaken from timbers of the choir, the north-east and south-east transepts, and the crossing between them in AD 1999 (Howard *et al* 2000). This work showed that major repairs took place here in the early-eighteenth century, again reusing some earlier timbers.

The programme of work reported upon here concerns the roof of St John Chapel, and the roof connecting the Chapel to the Chapter House, this latter known as "the connecting roof". The Laboratory was asked to sample timbers from both of these areas. The purpose of this work, also funded by English Heritage, was to inform the process of repair to the roofs which required the lifting of the lead covering and wooden boards beneath. Normally clear access to both these roofs is difficult, if not impossible, and these repairs provided a rare opportunity for investigation. A further purpose of the present analysis was to aid in the determination of the origin within the building of the re-used material. A plan of the Cathedral is shown in Figure 2.

The Laboratory would like to take this opportunity to thank all those who assisted with the sampling of the timbers. In particular thanks are due to the Dean and Chapter of Worcester Cathedral, the Clerk of Works, and to the Vergers' Office, whose staffs assisted with access to the roof. The Laboratory would also like to thank Mr Christopher Guy, the Cathedral Archaeologist, who made a detailed study of the roof, produced the drawings used in this report, and who assisted with the descriptive introduction to the site given above.

The roofs

For the purposes of this programme of analysis the Laboratory was asked to sample two different areas of the Cathedral; the roof of St John Chapel, and the roof connecting the Chapel to the Chapter House.

St John Chapel Roof

The Chapel roof contains five trusses consisting of tiebeams and principal rafters pitched at a shallow angle, see Figure 3. The principal rafters carry single purlins. Between the trusses the bays contain common rafters Upon examination the roof of St John Chapel appeared to contain five distinct sets of timbers. Primarily the roof contained a large number of well cut, reasonably square, timbers which showed no evidence of reuse. It was believed that these timbers belonged to a major reconstruction of this roof dated on the basis of documentary evidence to the eighteenth century. It was not certain, however, that all such timbers were contemporary.

Interspersed amongst these timbers were a smaller number of timbers less well cut and slightly more eroded. These showed evidence, by way of redundant mortices, peg holes, and lap joints of reuse.

In addition to these structural beams the roof was covered by two sets of wooden boards set beneath the lead. Some of these boards were of oak and some were of softwood.

Finally, once the lead of the guttering to St John Chapel was lifted an assortment of odd timbers were found, most of them showing clear evidence of having been used somewhere else first.

The connecting roof

The connecting roof, which is constructed of considerably fewer timbers than the chapel roof, appeared to contain a wide assortment of timbers. These ranged from more carefully cut and squared timbers with no obvious evidence of reuse and possibly contemporary with the existing structure, to those less well cut but showing no evidence of reuse, and those less well cut, rotted, and showing clear signs of a former life.

It is not clear whether the construction of the connecting roof is contemporary with the re-roofing of St John Chapel. Nor is it clear whether any of the reused timbers in either roof are of the same or similar date as each other. In short the two roofs contained timbers which could possibly have a very wide range of felling dates.

The construction of the connecting roof consists of a single pitch of common rafters, again set at a shallow angle, running from one main side wall to another. Many of these rafters are short, about 3 metres, whilst others are slightly longer, about 5 metres. The longer rafters are supported by cross-beams.

Sampling

After discussion with Chris Guy on the possible phasing of the building and on the timbers available, and in conjunction with the brief provided by English Heritage, a total of forty-three samples was obtained. Each sample was given the code WOR-C (for Worcester Cathedral). Given that coring etc from previous programmes of work totaled 98 samples it was decided to number the samples obtained for this piece of work from 101 – 143.

Twenty-three core samples, WOR-C101 – 123, were obtained from the structural timbers of St John Chapel roof. Given the uncertainty about the phasing of the timbers, no attempt was made to sample by any selective method other than their having a sufficient number of rings for dendrochronological analysis; samples were simply obtained from wide range of timbers

Nine core samples, WOR-C124 – 132, were obtained from the structural timbers of the connecting roof. Eight sliced samples, WOR-C133 – 140, were taken from the oak boards covering the St John Chapel roof. These eight samples were taken in a random method from a pile of oak boards which had been removed from the roof, discarded, and were not to be reused due to decay and splitting. None of the oak boards that were reused were sampled so that they would retain their maximum usable length.

Three of the ex-situ beams found beneath the guttering of the St John Chapel roof were also sampled as slices, these being WOR-C141 – 143.

In addition to the slices from the oak boards of St John Chapel roof, a random selection of non-oak boards were also sliced, producing six samples. These slices will be analysed and reported upon by the Sheffield Dendrochronology Laboratory and do not form part of this report.

This information given above is summarised below:

Sample area	Number of samples	Sample numbers
St John Chapel roof, structural timbers	23	WOR-C101 – 123
Connecting roof, structural timbers	9	WOR-C124 – 132
St John Chapel roof, oak covering boards	8	WOR-C133 – 140
St John Chapel roof, ex-situ beams	3	WOR-C141 – 143
St John Chapel roof, non-oak covering boards	6	No code

The positions of the cores from the structural timbers of St John Chapel and the connecting roofs were recorded at the time of sampling on survey plans produced and provided by Christopher Guy. These are reproduced here as Figures 4a/b. The positions of the *ex-situ* beam samples, the oak covering boards and the non-oak covering boards are not shown. Details of the samples are given in Table 1. Trusses, bays, and rafters etc have been numbered from north to south, or from east to west as the case may be.

Analysis

Each sample was prepared by sanding and polishing and the growth-ring widths of all forty-three were measured; the data of these measurements is given at the end of the report. All samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum t-value of 4.5 six groups of samples formed and were combined to form site chronologies. The six site chronologies were then compared with each other.

Two of these site chronologies had overlapping date spans and cross-matched with each other at relative positions consistent with their dating, with a *t*-value of 3.9. Because of this consistent cross-matching and dating, the samples in these two site chronologies were combined. When compared with the remaining ungrouped samples a further individual sample cross-matched with this group and it too was combined. None of the other site chronologies showed any cross-matching with each other.

The five site chronologies were compared with the nineteen remaining ungrouped samples. In no case was there any further satisfactory cross-matching. Each of the nineteen ungrouped samples with more than 54 rings, the minimum number of rings considered suitable for satisfactory analysis, was then compared with a full range of reference chronologies. While there was some possible cross-matching for some of the samples **(C26 last ring AD 1198, for Sheffield only)**, it was of limited replication and against non-local reference chronologies.

Brief details of these five site chronologies thus created are sumarised overpage.

Site chronology	Sample area	Number of samples	Number of rings	Date span
WORCSQ07	St John Chapel and connecting roofs	12	80	AD 1668 – 1746
WORCSQ08	St John Chapel and connecting roofs	4	131	AD 1286 – 1416
WORCSQ09	St John Chapel roof only	5	128	AD 1495 – 1622
WORCSQ10	St John Chapel roof ex-situ beams only	3	90	AD 1352 – 1441
WORCSQ11	St John Chapel roof oak boards	7	68	undated

Site chronologies WORCSQ07 and WORCSQ08 contain samples from structural timbers in both St John Chapel roof and the connecting roof. The other three site chronologies each consist of samples from discreet locations.

Bar diagrams of the samples in each site chronology are given in Figures 5 – 9, with evidence for the dating of those which cross-match with the reference chronologies being given in the *t*-values of Tables 2 – 5.

Interpretation

Site chronology WORCSQ07: samples from St John Chapel roof and the connecting roof; bar diagram Figure 5.

Eight of the twelve dated samples in site chronology WORCSQ07 are from various structural timbers of St John Chapel roof. The remaining four samples, WOR-C128, C129, C130, and C132, are from rafters of the connecting roof.

Five of the eight samples from St John Chapel roof have complete sapwood, that is, they retain the last growth-ring produced by the trees from which they were cut. Four of these five samples (WOR-C102, C104, C105, and C111) have last complete sapwood ring dates of AD 1743, and this is thus the felling date of the tree or trees represented. The fifth sample with complete sapwood from St John Chapel roof (WOR-C101) has a last measured complete sapwood ring date, and thus a felling date, of AD 1746

Two other samples (WOR-C103 and C107) from timbers with complete sapwood have lost only small portions from their sapwood during sampling and it is highly likely that these two were also felled in AD 1743. Only one sample, WOR-C108, has a slightly later heartwood/sapwood boundary than the others in this site chronology. It is possible that this sample also represents a tree felled in AD 1743, but it is perhaps more likely that it was felled in AD 1746.

The four samples from the connecting roof all have complete sapwood too. In one case, sample WOR-C128, the last measured complete sapwood ring date is AD 1743, the other three samples each have last measured complete sapwood ring dates of AD 1746. These are thus the felling dates of the timbers represented by these samples.

Site chronology WORCSQ08: samples from St John Chapel roof and the connecting roof; bar diagram Figure 6.

Two of the samples in this site chronology, WOR-C112 and WOR-C117, come from structural timbers of St John Chapel roof, a common rafter and a purlin respectively. The other two samples, WOR-C124 and WOR-C125, are from structural timbers, the main north and main south bridging beams, of the connecting roof. Hence to begin with we consider these two pairs of samples separately.

Sample WOR-C112 has a heartwood/sapwood transition date of AD 1389, while sample WOR-C117 does not, its last measured heartwood ring dating to AD 1364. The usual 95% confidence limit for the amount of sapwood on mature oaks in this part of England is 15 – 50 rings. Such a limit would give the timbers represented by these two samples an estimated felling date in the range AD 1404 – 39.

Sample WOR-C124 does not have the heartwood/sapwood boundary and its last measured heartwood ring is dated to AD 1388. Sample WOR-C125 does have a heartwood/sapwood boundary, this being dated to AD 1416. Using the same sapwood limit as above would give the timbers represented by these two samples an estimated felling date range of AD 1431 – 66. Thus while it is possible that two separate fellings are represented it is also possible that the timbers represented by these two pairs of samples were both felled at the same time in the period AD 1431 – 39, where the estimated felling date ranges overlap with each other.

Site chronology WORCSQ09: samples from St John Chapel roof only, bar diagram Figure 7.

All five samples in this site chronology are from common rafters in the roof of St John Chapel. Three of them come from timbers which had complete sapwood but of which portions were lost during coring. Observations and notes made at the time of sampling indicate that the lost portion of sapwood probably represents 8 – 12 rings. The relative positions of the heartwood/sapwood boundaries on three of the samples at least are consistent with timbers having a single felling. Given that the last ring date of the site chronology is AD 1622, the felling date for the timbers represented is estimated be *c* AD 1635 and certainly no later than AD 1640

The only difficulty in this interpretation may lie with sample WOR-C118. This sample does not have a heartwood/sapwood boundary. It is unlikely to have been felled before AD 1619, and given that there are no structural or carpentry indications to the contrary, there is no reason why it too was not felled at the same time as the other timbers represented in site chronology WORCSQ09.

Site chronology WORCSQ10: St John Chapel roof ex-situ beams only, bar diagram Figure 8

The three samples in site chronology WORCSQ10, WOR-C141, C142, and C143, are all from the timbers found supporting the gutter beneath the lead of St Chapel roof. None of them have a heartwood/sapwood boundary and it is thus not possible to estimate their felling date. However, given that the beams are probably from the same tree and that the latest dated ring on any of them is AD 1441, it is unlikely that they were felled before *c* AD 1456.

Site chronology WORCSQ11: St John Chapel roof oak boards, bar diagram, Figure 9

Four of the eight samples sliced from the oak boards covering the roof of St John Chapel cross-matched with each other to form this site chronology. The relative positions of the heartwood/sapwood boundaries on the four samples strongly suggest that they represent timbers with a single felling. However, the estimated date of this felling cannot be ascertained because, although compared with a wide range of reference chronologies there was no cross-matching. These samples must, therefore, remain undated.

Conclusion

This analysis has been able to date timbers from a number of distinct groups found in the St John Chapel roof and the connecting roof. As suspected on carpentry and structural ground, however, these groups of timbers do have a wide spread of felling dates indicating extensive reuse. It may be possible to further refine the dates obtained by dendrochronology if they can be linked with documentary information for repair or modification. This may aid in the identification of the source roof, or roofs, from which the material reused here was taken.

St John Chapel roof

At least five possible phases of timber felling have been identified in this roof. It would appear that a quantity of timber in St John Chapel roof was felled in AD 1743, as represented by four of the twelve samples in site chronology WORCSQ07. Two further timbers were probably felled at this time also, though they might have been felled a few years later.

One timber from this roof was definitely felled in AD 1746, with another timber probably being felled at this time. We thus detect the possibility that some timber, those pieces felled in AD 1743, was stored for a few years before it was used along with the timber felled in AD 1746. This being the latest date of any of the samples analysed and there being no evidence for reuse of such timbers may represent the Chapel's last major re-roofing.

The Chapel roof, however, also contains a timber that could have been felled as early as AD 1379, although its true felling date cannot be reliably estimated, and a timber with an estimated felling date in the range AD 1404 – 39. These dates are represented by samples WOR-C117 and WOR-C112, respectively, in site chronology WORCSQ08. The roof also contains timbers estimated to have been felled *c* AD 1635 – 40, as represented by site chronology WORCSQ09.

The Chapel also contained some loose *ex-situ* timbers beneath its guttering. While the felling dates of these cannot be accurately estimated they cannot have been before the middle of the fifteenth-century. The oak boards from this roof have not been dated.

Connecting roof

At least two phases of felling have been identified in the connecting roof, although fewer timbers have been dated. One of these samples, WOR-C128, from a rafter, retains complete sapwood with a last measured ring date, and thus a felling date, of AD 1743. Four other samples retain complete sapwood with last measured ring dates of AD 1476.

A second sample, WOR-C125, from one of the bridging beams, suggests that the timber represented has a felling date in the range AD 1431 – 66. A timber that might have a similar estimated felling date range is also found in the Chapel roof.

The felling date of the third dated timber from the connecting roof cannot be estimated, but is unlikely to have been before AD 1403.

This felling date information is summarised overage.

Sample source	Samples	Estimated felling date range
St John Chapel roof, structural timbers	C101, C108	AD 1746
	C102, C103, C104, C105, C107, C111	AD 1743
St John Chapel roof, structural timbers	C106, C115, C116, C118, C122	AD 1635 – 40
St John Chapel roof, *ex-situ* beams	C141, C142, C143	not before AD 1456
St John Chapel roof, single structural timber	C112	AD 1404 – 39
St John Chapel roof, single structural timber	C117	not before AD 1379
Connecting roof, single rafter	C128	AD 1743
Connecting roof, rafters	C129, C130, C132	AD 1746
Connecting roof, bridging beam	C125	AD 1431 – 66
Connecting roof, bridging beam	C124	not before AD 1403

Twelve ungrouped samples remain undated. Only half a dozen of these have a sufficient number of rings for reliable dating. None of these show any major problems, though some of them do show slightly complacent growth. This, and the fact that, given the wide range of felling dates obtained for the timber in these roofs, they may in effect be singletons which are always more difficult to date, may account for their lack of cross-matching.

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Table 1: Details of samples from the roof of St John's Chapel and the connecting roof at Worcester Cathedral, Worcester

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	St John Chapel roof					
WOR-C101	Ridge beam, east gable – truss 1	53	19C	AD 1694	AD 1727	AD 1746
WOR-C102	Tiebeam, truss 1	65	16C	AD 1679	AD 1727	AD 1743
WOR-C103	Ridge beam, truss 1 – 2	62	14c	AD 1677	AD 1724	AD 1738
WOR-C104	North purlin, truss 1 – 2	57	19C	AD 1687	AD 1724	AD 1743
WOR-C105	North purlin, truss 2 – 3	77	24C	AD 1667	AD 1719	AD 1743
WOR-C106	Ridge beam, truss 2 – 3	98	20	AD 1518	AD 1595	AD 1615
WOR-C107	South purlin, truss 2 – 3	63	16c	AD 1677	AD 1723	AD 1739
WOR-C108	Tiebeam, truss 3	63	h/s	AD 1668	AD 1730	AD 1730
WOR-C109	North common rafter 10 from east	106	24C	------	------	------
WOR-C110	South wall plate, truss 1 – 3	61	h/s	------	------	------
WOR-C111	North purlin, north gable – truss 1	71	22C	AD 1673	AD 1721	AD 1743
WOR-C112	South purlin, north gable – truss 1	86	3	AD 1307	AD 1389	AD 1392
WOR-C113	South common rafter 24 from east	73	no h/s	------	------	------
WOR-C114	South common rafter 23 from east	50	no h/s	------	------	------
WOR-C115	South common rafter 20 from east	79	10c	AD 1544	AD 1612	AD 1622
WOR-C116	South common rafter 19 from east	126	12c	AD 1495	AD 1608	AD 1620
WOR-C117	South common rafter 18 from east	79	no h/s	AD 1286	------	AD 1364
WOR-C118	South common rafter 15 from east	67	no h/s	AD 1538	------	AD 1604
WOR-C119	South common rafter 14 from east	60	no h/s	------	------	------
WOR-C120	North common rafter 8 from east	44	14c	------	------	------
WOR-C121	South common rafter 4 from east	38	no h/s	------	------	------
WOR-C122	South common rafter 2 from east	67	12c	AD 1556	AD 1610	AD 1622
WOR-C123	North common rafter 1 from east	48	no h/s	------	------	------

Table 1: Continued

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Connecting roof					
WOR-C124	Main east bridging beam	98	no h/s	AD 1291	------	AD 1388
WOR-C125	Main west bridging beam	114	h/s	AD 1303	AD 1416	AD 1416
WOR-C126	Timber reused as south-east wall plate	86	h/s	------	------	------
WOR-C127	Rafter 5 from north	49	h.s	------	------	------
WOR-C128	Rafter 6 from north	63	22C	AD 1681	AD 1721	AD 1743
WOR-C129	Rafter 7 from north	54	19C	AD 1693	AD 1727	AD 1746
WOR-C130	Rafter 10 from north	45	16C	AD 1702	AD 1730	AD 1746
WOR-C131	Rafter 11 from north	38	15C	------	------	------
WOR-C132	Rafter 12 from north	45	16C	AD 1702	AD 1730	AD 1746
	St John Chapel Roof					
WOR-C133	Board	54	no h/s	------	------	------
WOR-C134	Board	48	no h/s	------	------	------
WOR-C135	Board	54	no h/s	------	------	------
WOR-C136	Board	56	no h/s	------	------	------
WOR-C137	Board	57	h/s	------	------	------
WOR-C138	Board	61	4	------	------	------
WOR-C139	Board	61	6	------	------	------
WOR-C140	Board	54	h/s	------	------	------

Table 1: Continued

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	St John Chapel Roof					
WOR-C141	Loose timber beneath gutter	90	no h/s	AD 1352	------	AD 1441
WOR-C142	Loose timber beneath gutter	80	no h/s	AD 1357	------	AD 1436
WOR-C143	Loose timber beneath gutter	66	no h/s	AD 1360	------	AD 1425

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

Table 2: Results of the cross-matching of site chronology WORCSQ07 and relevant reference chronologies when first ring date is AD 1667 and last ring date is AD 1743

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	5.9	(Laxton and Litton 1988)
England	AD 401 – 1981	4.7	(Baillie and Pilcher 1982 unpubl)
England, London	AD 413 – 1728	3.6	(Tyers and Groves 1999 unpubl)
Worcester Cathedral, Nave roof	AD 1597 – 1730	5.6	(Howard *et al* 1995)
Quenby Hall, Leics	AD 1648 – 1765	6.9	(Howard *et al* 1993 unpubl)
Catholme, Staffs	AD 1649 – 1750	5.8	(Howard *et al* 1992 unpubl)
Sutton in Ashfield, Notts	AD 1441 – 1656	5.0	(Howard *et al* 1996a)

Table 3: Results of the cross-matching of site chronology WORCSQ08 and relevant reference chronologies when first ring date is AD 1286 and last ring date is AD 1416

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	8.0	(Laxton and Litton 1988)
England	AD 401 – 1981	6.9	(Baillie and Pilcher 1982 unpubl)
England, London	AD 413 – 1728	7.7	(Tyers and Groves 1999 unpubl)
Mercers Hall, Gloucester	AD 1289 – 1541	5.8	(Howard *et al* 1997)
Newton Linford, Leics	AD 1319 – 1437	7.4	(Alcock *et al* 1990)
Stowemarket Church, Suffolk	AD 1251 – 1363	6.5	(Howard *et al* 1994)
Chesterfield, Derbys	AD 1212 – 1332	5.3	(Howard *et al* 1996b)

Table 4: Results of the cross-matching of site chronology WORCSQ09 and relevant reference chronologies when first ring date is AD 1495 and last ring date is AD 1622

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	7.5	(Laxton and Litton 1988)
England	AD 401 – 1981	7.8	(Baillie and Pilcher 1982 unpubl)
MC10---H	AD 1386 – 1585	8.5	(Fletcher 1978 unpubl)
Wales and West Midlands	AD 1341 – 1636	8.1	(Siebenlist-Kerner 1978)
Sinai Park, Staffs	AD 1227 – 1750	6.3	(Tyers 1997)
England, London	AD 413 – 1728	5.4	(Tyers and Groves 1999 unpubl)
26 Westgate St, Gloucester	AD 1399 – 1622	9.2	(Howard *et al* forthcoming)

Table 5: Results of the cross-matching of site chronology WORCSQ10 and relevant reference chronologies when first ring date is AD 1352 and last ring date is AD 1441

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	5.3	(Laxton and Litton 1988)
England	AD 401 – 1981	6.7	(Baillie and Pilcher 1982 unpubl)
England, London	AD 413 – 1728	5.8	(Tyers and Groves 1999 unpubl)
Wales and West Midlands	AD 1341 – 1636	5.9	(Siebenlist-Kerner 1978)
MC10---H	AD 1386 – 1585	5.6	(Fletcher 1978 unpubl)
Mercers Hall, Gloucester	AD 1289 – 1541	9.8	(Howard *et al* 1997)
Lodge Park, Aldsworth, Glos	AD 1324 – 1587	5.6	(Howard *et al* 1995)
Southern England	AD 1083 – 1589	5.2	(Bridge 1988)

Figure 1: Map to show general location of Worcester Cathedral

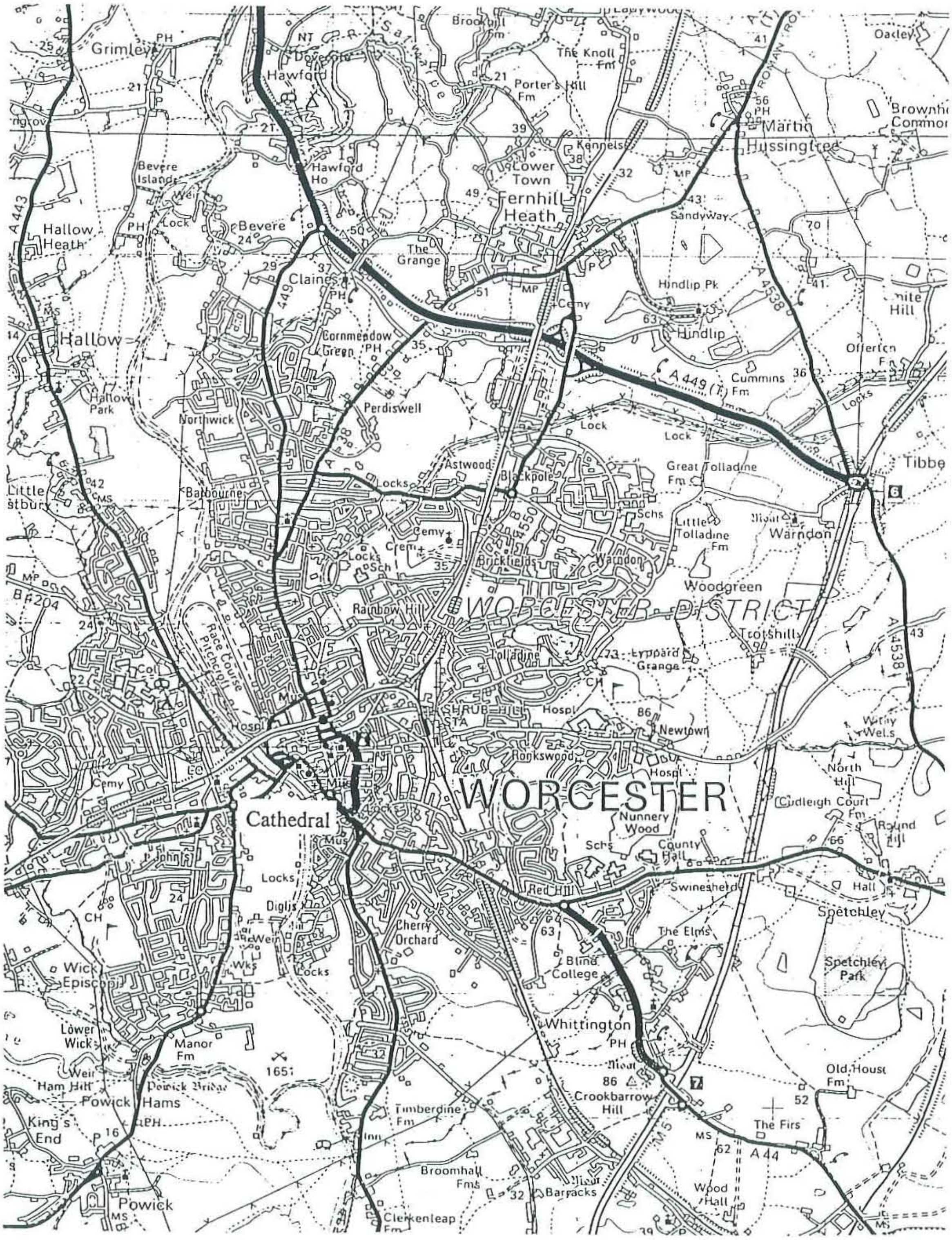


Figure 2: Plan showing the layout of the cathedral with St John Chapel and the connecting roof being shaded

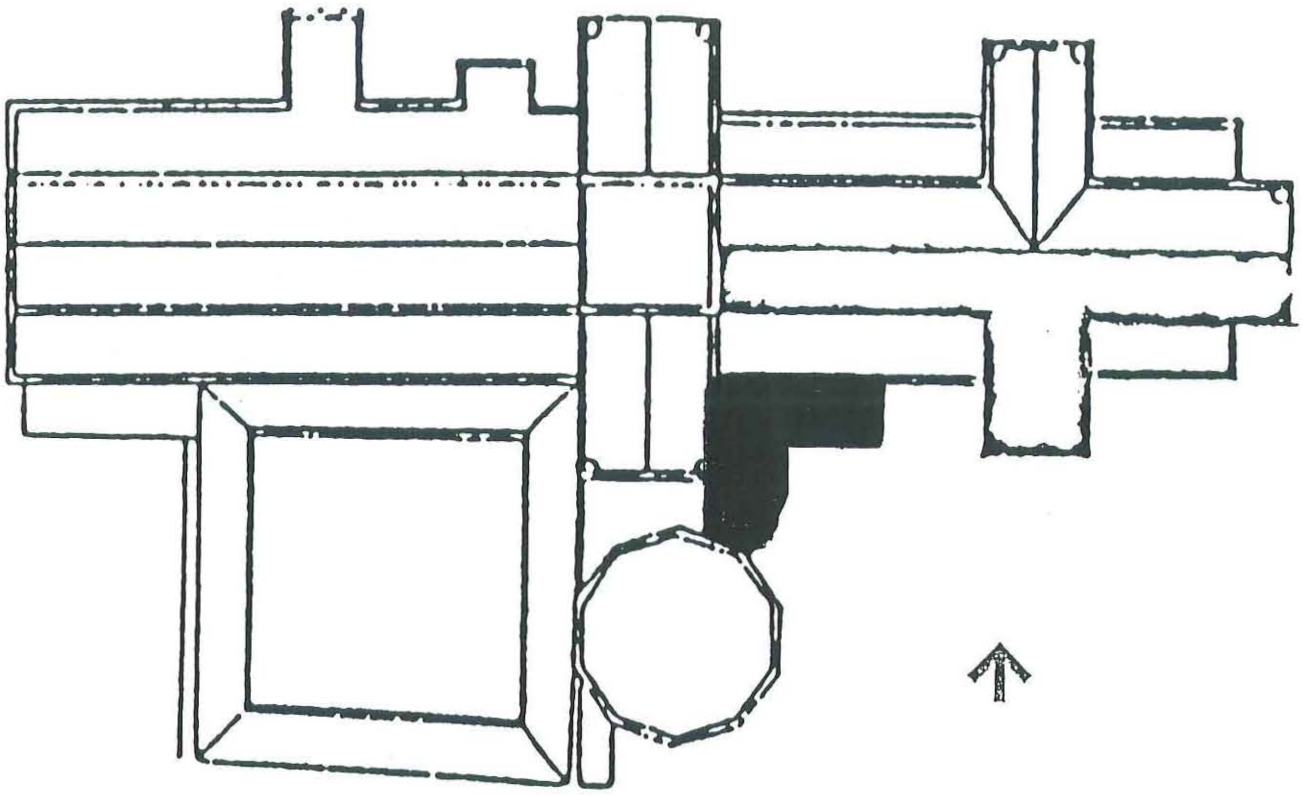
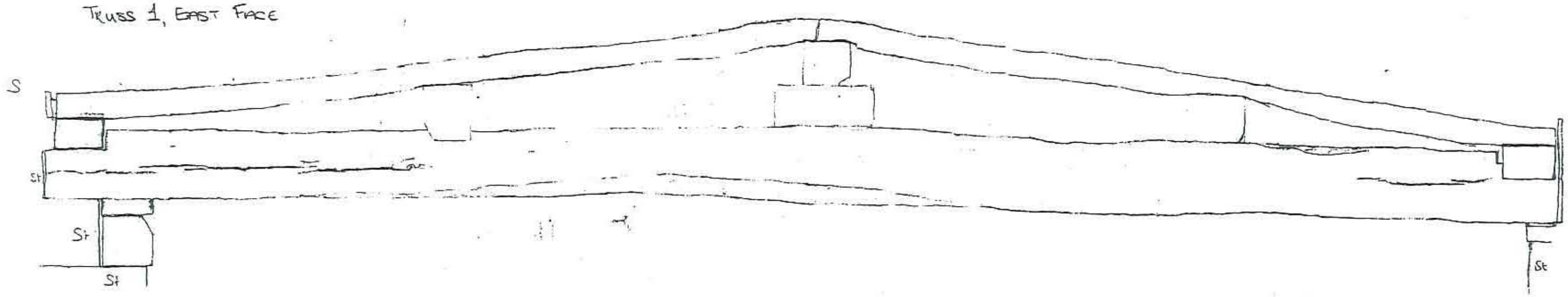


Figure 3: Drawing showing the east face of trusses 1 and 2 in St John Chapel roof



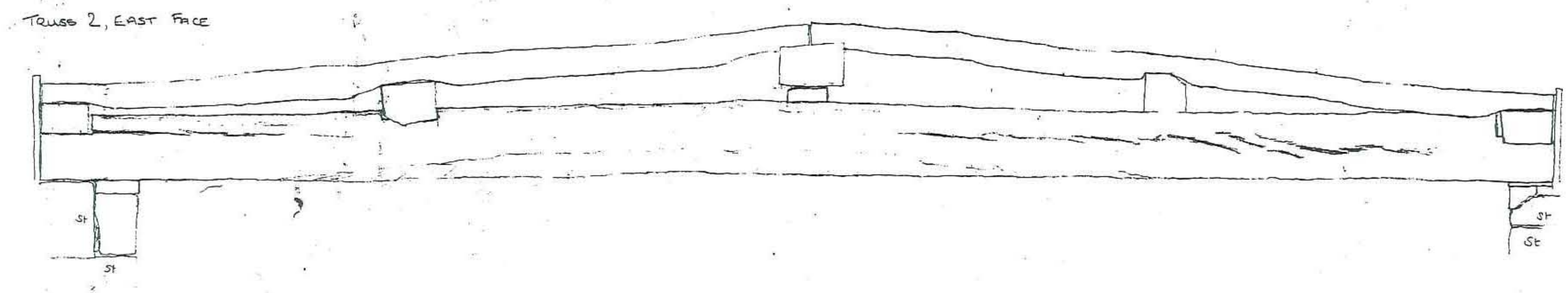


Figure 5: Bar diagram of samples in site chronology WORCSQ07

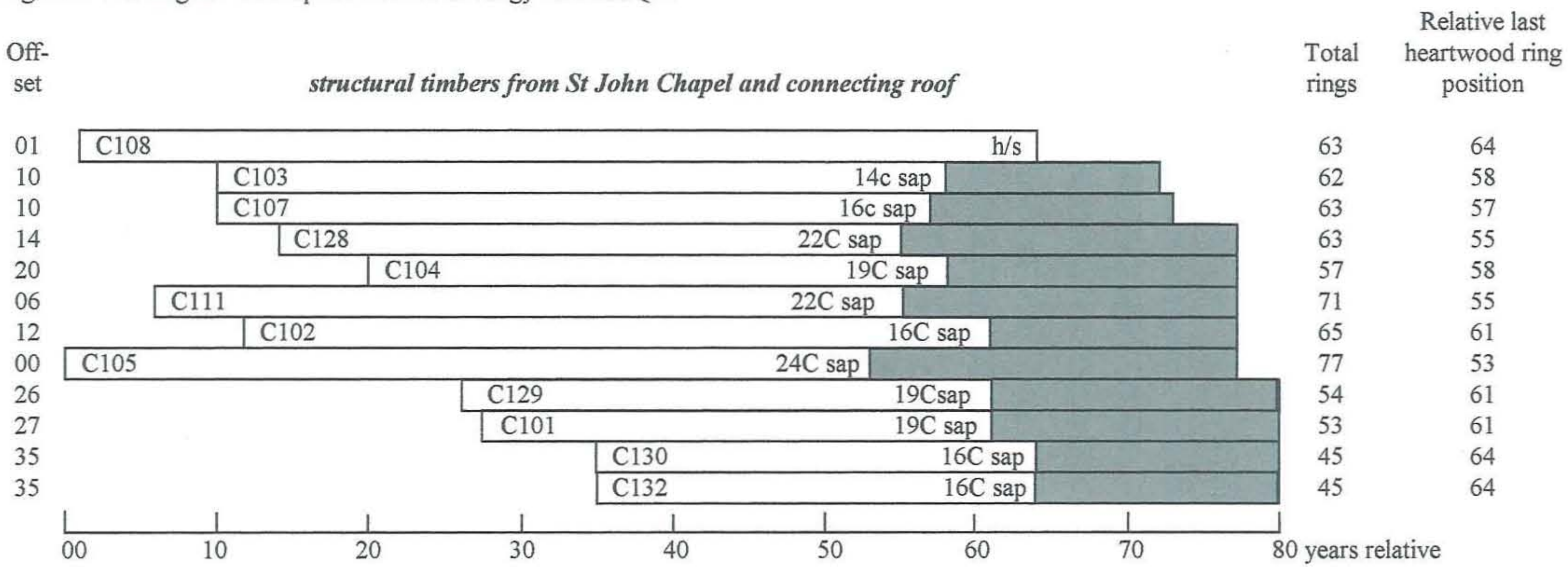


Figure 6: Bar diagram of samples in site chronology WORCSQ08

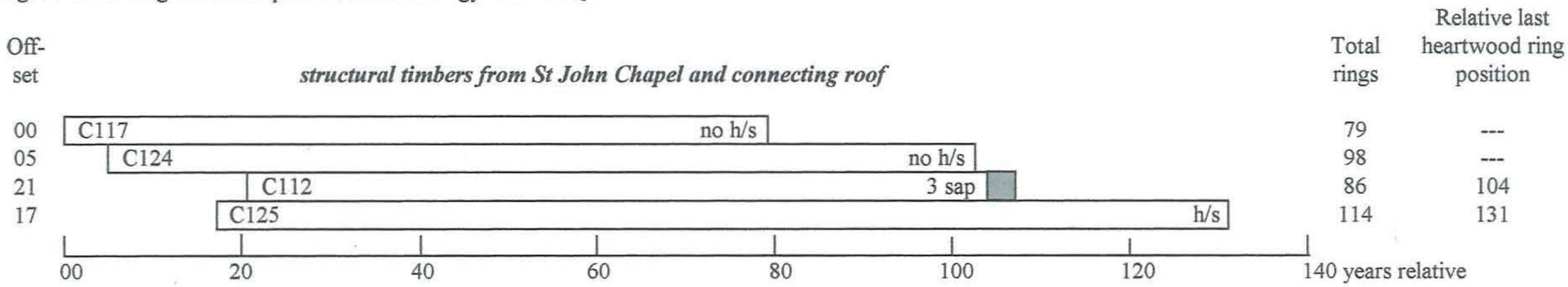


Figure 7: Bar diagram of samples in site chronology WORCSQ09

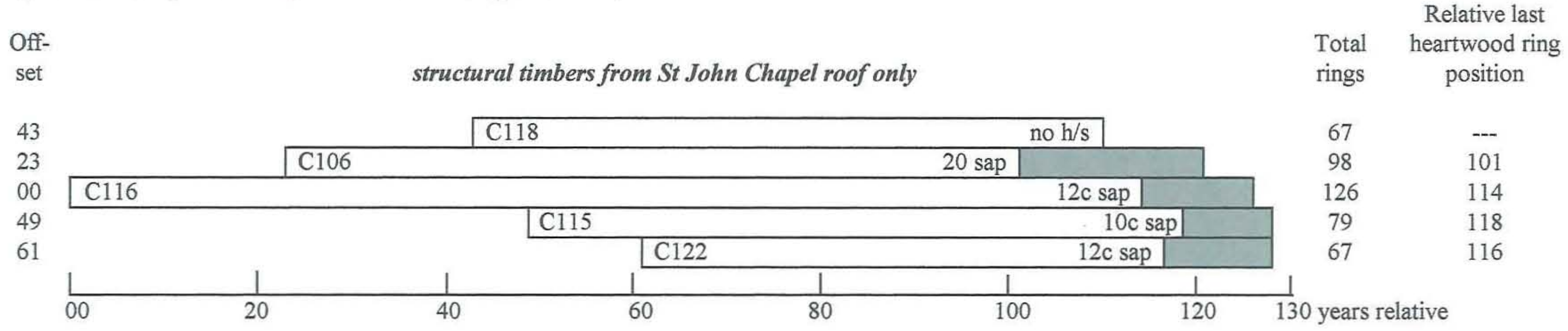


Figure 8: Bar diagram of samples in site chronology WORCSQ10

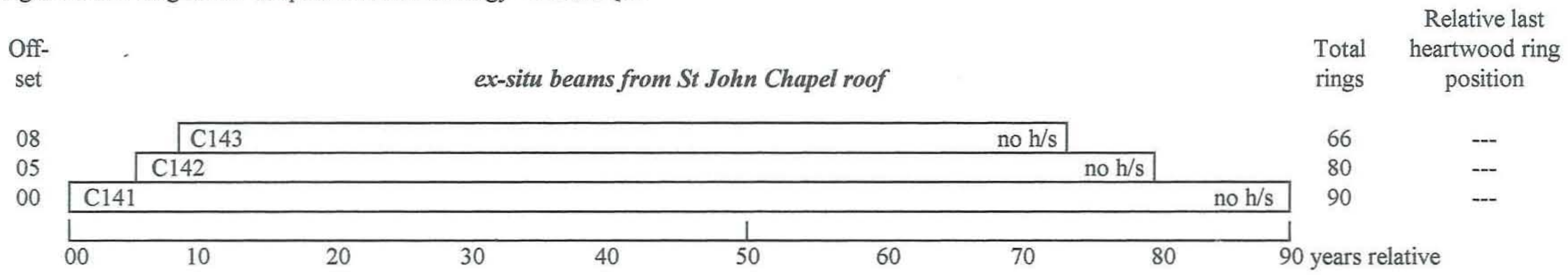
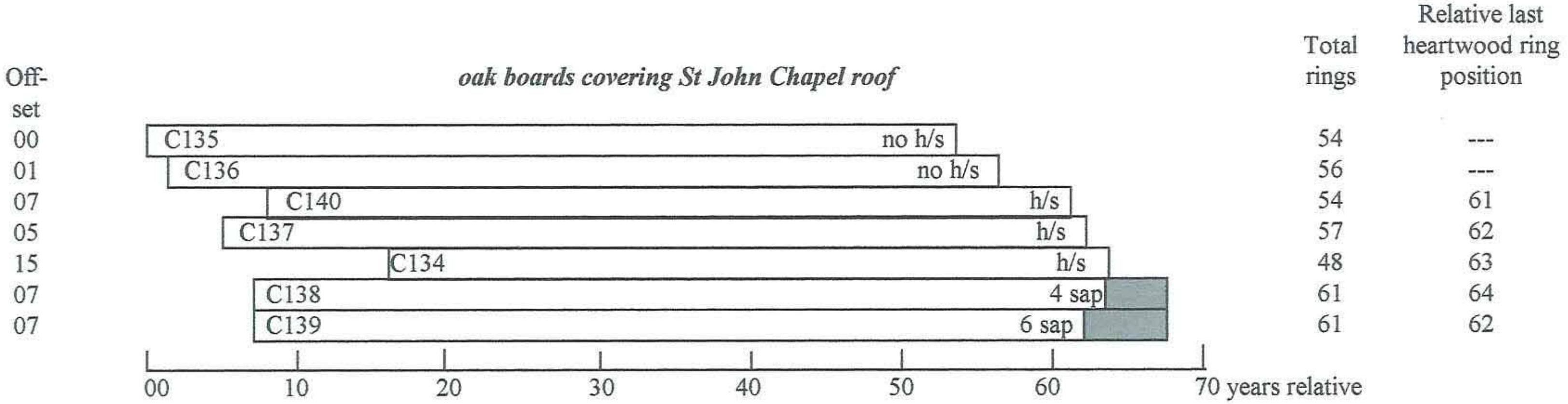


Figure 9: Bar diagram of samples in site chronology WORCSQ011



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
c = complete sapwood on timber, all or part lost in coring
C = complete sapwood retained on sample

Data of measured samples – measurements in 0.01 mm units

WOR-C101A 53
396 508 492 417 521 394 424 444 419 456 401 280 458 356 341 341 267 383 372 388
295 310 323 288 238 265 260 256 261 232 349 266 336 361 324 222 219 209 315 231
282 410 309 268 402 317 273 265 208 290 353 240 180
WOR-C101B 53
388 524 542 431 522 402 434 451 418 426 396 268 485 350 342 346 240 365 379 409
284 326 322 302 227 274 258 265 255 237 340 270 322 360 304 214 228 221 320 235
272 414 324 266 395 348 254 259 229 295 330 251 193
WOR-C102A 65
350 384 275 362 361 246 270 352 216 212 235 231 327 270 282 290 273 314 307 301
234 293 322 270 318 290 184 274 224 257 246 207 177 224 233 154 175 203 200 168
176 167 152 149 127 182 194 236 196 225 200 178 174 163 167 201 252 247 215 248
280 219 216 154 182
WOR-C102B 65
347 375 279 380 345 249 247 359 217 209 232 242 322 277 282 273 268 302 297 305
248 297 325 273 323 292 190 272 218 255 247 194 189 235 235 153 169 197 201 184
196 172 142 155 123 172 190 238 170 208 168 219 158 185 158 182 277 245 209 252
290 211 182 159 182
WOR-C103A 62
96 270 231 670 553 488 449 292 403 397 236 177 309 209 242 154 267 276 190 264
209 358 224 247 270 216 225 270 190 278 220 225 222 172 169 175 217 176 194 176
135 102 127 141 119 148 115 142 142 136 146 136 151 130 129 161 162 173 220 252
255 236
WOR-C103B 62
145 329 278 596 560 486 446 290 407 392 232 186 310 202 243 171 261 286 185 272
211 351 213 241 268 211 233 273 183 268 217 239 227 177 174 172 220 172 187 194
127 103 130 132 126 147 109 159 143 146 134 142 151 124 128 174 163 167 229 247
240 226
WOR-C104A 57
482 454 479 426 549 425 473 561 453 447 387 485 327 382 438 254 297 371 201 342
253 225 227 183 224 205 195 138 189 174 187 196 216 223 179 199 158 271 173 212
223 208 162 176 129 191 147 158 222 202 144 195 214 164 157 212 160
WOR-C104B 57
495 421 470 434 507 436 473 551 471 443 359 445 327 410 426 283 340 365 210 331
242 236 245 179 231 221 183 155 168 153 187 190 210 208 177 197 149 274 171 219
211 190 168 180 138 184 143 164 231 201 138 189 232 148 168 202 159
WOR-C105A 77
386 458 383 347 486 347 420 243 255 219 359 367 495 446 261 250 180 223 199 306
211 203 302 285 259 281 287 240 213 257 240 211 203 235 208 154 186 211 139 224
187 193 256 153 196 223 260 159 188 259 232 188 205 135 142 148 130 221 99 62
117 74 95 91 89 104 88 87 96 107 112 124 128 130 106 124 132
WOR-C105B 77
340 453 383 351 448 341 450 233 235 204 375 344 462 448 283 240 157 207 172 302
191 215 293 266 269 301 303 229 234 250 254 221 199 230 209 157 177 208 130 210
198 197 251 139 207 215 277 155 192 251 236 189 205 125 153 148 132 214 99 60
116 102 72 90 86 110 78 99 91 110 107 127 134 132 111 115 134

WOR-C106A 98
174 188 159 225 185 136 156 137 160 156 164 150 142 208 120 104 108 137 65 90
71 79 95 122 102 121 112 100 66 102 251 374 336 398 277 258 263 284 187 164
80 115 148 156 249 173 180 189 161 177 152 249 217 219 197 240 213 135 86 115
157 168 280 204 224 212 217 309 243 289 292 278 189 247 215 250 272 242 202 207
217 223 169 247 246 242 219 173 192 226 234 207 225 214 158 238 202 282
WOR-C106B 98
161 183 162 226 192 134 164 131 161 164 174 151 140 192 130 100 101 114 75 90
72 75 106 140 102 119 116 103 69 93 262 361 345 395 271 270 265 278 190 163
80 113 145 159 254 178 175 184 156 180 150 250 220 209 208 241 206 132 91 112
170 168 275 208 234 204 209 312 253 276 293 297 177 246 209 265 265 248 203 206
214 221 178 233 256 242 231 156 187 230 244 195 243 211 161 223 207 282
WOR-C107A 63
375 434 300 213 113 138 159 169 150 218 115 117 88 134 159 151 248 286 317 305
360 329 278 377 321 206 198 264 162 257 220 288 376 202 223 223 280 157 234 244
223 189 176 162 126 145 139 195 130 76 94 89 110 143 135 140 126 115 104 114
83 127 158
WOR-C107B 63
347 397 309 217 117 133 152 171 147 215 120 121 86 96 161 156 232 268 312 281
355 311 290 373 313 213 188 277 153 257 231 289 384 199 223 232 276 134 257 244
223 185 173 170 114 153 137 196 134 74 91 96 105 147 132 149 123 113 105 102
91 121 154
WOR-C108A 63
109 144 167 281 120 206 91 88 145 227 241 306 314 222 264 293 217 186 348 255
325 296 403 438 417 396 448 380 358 332 338 233 329 365 300 359 384 223 339 310
319 282 173 235 279 352 235 373 237 203 163 224 225 257 185 203 369 388 394 366
279 262 233
WOR-C108B 63
136 135 176 263 174 180 106 89 120 201 238 273 283 215 285 301 230 197 331 256
328 308 405 431 409 407 434 395 353 335 342 231 311 333 302 365 381 208 338 310
318 277 181 226 285 367 230 365 245 198 172 225 230 258 184 195 346 400 400 375
277 262 254
WOR-C109A 106
333 405 269 245 273 258 316 293 246 209 272 181 139 167 213 204 244 213 199 227
226 211 219 196 140 138 192 145 153 117 136 158 148 139 135 162 89 121 123 141
153 155 207 203 162 151 115 151 125 155 179 99 60 39 47 34 50 61 57 54
72 104 94 99 98 110 149 145 145 97 100 98 95 111 109 141 78 72 87 91
79 78 55 77 129 174 188 85 120 94 101 91 129 88 124 92 127 131 158 102
110 154 99 140 139 153
WOR-C109B 106
307 408 274 238 280 260 311 298 253 231 287 164 136 160 200 215 234 223 189 235
213 213 228 199 145 128 186 146 153 114 139 158 142 141 129 168 85 126 122 144
151 165 202 206 171 154 115 143 133 149 166 95 49 38 43 39 51 62 55 63
67 98 96 104 96 107 155 146 139 104 99 109 95 108 111 134 81 84 86 90
63 85 67 76 155 148 172 105 111 101 93 93 150 89 150 70 122 125 161 102
101 160 101 141 143 126
WOR-C110A 61
312 438 523 543 445 484 467 402 427 431 307 378 580 400 502 321 605 401 268 289
400 349 241 351 313 392 357 371 369 265 312 248 226 284 154 149 169 149 163 180
212 264 182 190 173 265 214 171 203 202 194 177 239 277 275 254 202 142 146 191
264

WOR-C110B 61
303 449 469 553 454 476 476 400 435 387 325 375 571 381 477 326 586 444 276 261
422 327 237 357 320 397 375 353 369 249 297 270 229 305 148 143 171 138 170 178
211 273 176 198 172 277 200 177 203 201 190 174 241 263 272 270 194 147 141 190
251
WOR-C111A 71
328 245 338 336 398 433 608 450 358 283 199 323 232 296 193 217 307 294 389 348
381 330 356 318 334 280 282 331 321 228 229 298 196 248 234 270 301 179 203 193
269 166 219 185 213 192 202 124 109 124 109 148 52 37 35 33 45 79 129 149
121 99 120 131 165 147 174 133 139 157 105
WOR-C111B 71
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386 325 343 329 333 282 284 329 313 238 231 301 198 242 247 259 289 154 222 191
261 164 211 190 213 186 213 131 116 123 102 158 66 29 38 31 41 77 132 130
119 103 103 147 167 151 181 122 145 160 104
WOR-C112A 86
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182 201 167 161 116 110 137 135 196 109 130 96 146 141 127 140 181 96 113 169
255 305 366 260 297 176 217 219 133 148 188 174 193 121 134 173 237 258 151 172
136 130 218 240 197 217 217 245 233 211 178 185 306 233 174 175 176 163 204 258
248 206 185 123 189 145
WOR-C112B 86
229 222 216 216 230 201 172 220 256 243 219 183 216 170 205 217 174 154 96 76
175 208 171 161 118 107 128 120 190 120 121 89 149 126 120 151 179 79 127 184
270 313 346 274 285 173 225 222 130 150 196 182 175 105 138 163 257 263 158 177
128 147 227 223 191 232 213 232 249 203 170 187 310 223 173 172 182 166 206 258
239 197 192 134 181 148
WOR-C113A 73
236 198 220 204 235 241 251 433 316 340 485 449 508 469 240 252 369 338 328 350
435 358 372 367 362 370 357 288 284 270 214 148 149 207 200 157 134 126 154 61
78 86 129 123 135 137 124 128 133 140 252 271 219 142 117 154 144 128 155 182
125 155 200 192 218 153 155 260 350 364 225 272 174
WOR-C113B 73
264 197 224 212 220 232 272 417 351 320 472 468 492 465 243 251 377 324 331 344
446 356 341 380 342 358 342 280 274 264 204 152 150 202 210 162 139 135 144 67
74 83 128 126 136 130 117 121 138 138 253 271 219 129 128 154 157 141 134 158
129 136 197 183 203 145 142 206 386 361 236 269 210
WOR-C114A 50
216 284 392 356 396 318 371 317 283 208 231 285 224 264 254 277 226 222 220 210
187 179 163 165 172 206 135 172 206 167 137 227 162 181 100 140 161 151 161 147
143 142 153 125 108 136 108 89 83 118
WOR-C114B 50
221 290 414 361 385 335 371 321 289 196 238 288 219 262 246 280 217 257 225 238
185 183 166 153 175 201 140 168 208 164 140 225 163 181 98 131 172 149 161 148
140 147 148 115 118 134 106 83 110 104
WOR-C15A 79
178 232 205 204 211 305 281 287 233 187 223 265 174 148 111 112 153 197 184 181
200 211 201 401 251 230 234 264 173 240 214 232 141 130 123 144 220 201 213 194
237 207 242 237 196 232 135 138 193 209 231 216 162 286 313 248 215 226 292 257
214 172 247 283 242 182 182 178 156 193 201 275 357 280 277 178 332 322 257

WOR-C115B 79
162 230 209 200 213 303 279 290 230 185 221 268 177 133 108 113 157 193 185 182
217 214 206 390 247 239 233 280 183 223 208 231 143 129 135 159 247 228 205 178
244 225 255 218 221 220 135 139 194 217 216 215 160 289 314 248 217 220 288 260
205 175 260 282 239 184 184 173 153 199 197 279 354 270 287 177 348 296 287
WOR-C116A 126
214 250 205 150 218 302 265 291 205 208 336 262 301 185 279 201 194 170 250 147
274 273 187 150 305 175 247 302 188 203 119 144 159 328 242 160 282 187 129 135
216 172 168 133 137 176 218 142 183 163 143 96 69 86 50 53 148 89 119 101
163 72 49 49 76 112 93 167 77 138 105 59 47 68 151 152 139 69 68 55
78 74 88 72 98 153 107 71 79 127 136 84 109 105 130 55 72 53 54 78
79 80 53 70 61 56 81 112 87 101 86 119 110 135 116 62 65 51 93 54
55 55 60 59 75 73
WOR-C116B 126
211 261 208 158 216 312 268 297 201 212 337 280 309 200 268 210 196 177 251 147
293 262 233 158 345 169 241 306 189 213 126 141 168 308 244 158 282 180 149 129
214 180 169 150 125 179 221 157 184 152 130 91 70 88 36 52 141 96 116 111
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80 68 89 77 91 159 111 73 74 132 133 82 111 102 128 68 68 58 51 77
84 72 58 69 63 56 76 115 89 97 78 133 111 131 117 68 66 50 86 62
50 55 64 60 75 73
WOR-C117A 79
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226 261 229 191 240 204 156 164 262 312 258 200 180 256 229 285 263 270 203 131
116 235 214 142 160 172 160 121 133 232 201 147 194 207 148 160 120 134 123 197
208 148 228 247 132 134 87 139 196 103 88 183 177 158 76 76 124 210 180
WOR-C117B 79
262 166 217 291 345 261 353 407 425 212 245 315 185 152 271 349 304 267 273 283
226 258 223 198 241 201 170 157 264 314 269 204 168 246 234 293 269 262 218 114
117 227 216 148 161 169 147 131 137 235 200 148 188 207 155 154 136 128 124 193
211 149 230 243 132 127 94 140 197 93 92 196 170 150 81 78 116 213 193
WOR-C118A 67
183 201 198 196 142 189 143 243 81 70 75 122 142 246 145 143 181 260 279 110
85 117 141 139 123 213 249 201 207 202 282 286 112 111 87 136 146 151 84 68
64 79 64 47 53 55 81 71 74 89 103 63 52 35 63 53 63 48 55 69
103 81 55 42 25 54 51
WOR-C118B 67
189 200 209 189 146 192 149 241 84 70 76 123 140 225 150 145 178 248 301 104
100 98 156 134 121 201 226 240 198 210 287 255 124 117 87 140 136 154 82 67
69 78 64 46 56 55 76 64 79 86 104 73 43 38 67 47 63 55 49 75
98 84 49 46 31 45 52
WOR-C119A 60
245 203 169 137 143 194 208 180 169 167 190 165 151 186 193 211 233 225 162 249
264 211 181 170 130 143 124 140 134 156 172 143 206 141 164 120 173 189 143 133
125 142 178 117 234 265 252 229 192 220 236 237 243 172 202 181 249 182 144 126
WOR-C119B 60
260 200 172 139 137 200 234 190 174 170 182 171 141 186 179 219 243 226 169 247
262 212 188 163 137 146 118 142 137 158 182 134 212 148 161 125 167 186 135 140
135 146 180 128 234 275 237 237 196 215 237 217 256 171 199 188 250 178 137 129

WOR-C120A 44
511 359 305 275 258 256 201 386 304 454 363 258 166 223 270 193 502 263 276 251
323 215 199 174 241 347 273 318 228 250 310 164 202 254 180 318 224 300 203 197
213 168 205 246
WOR-C120B 44
546 366 321 280 245 256 196 386 298 452 347 256 174 227 278 188 484 274 280 253
324 206 203 179 237 349 277 304 230 248 309 173 214 237 190 318 246 278 196 191
206 165 221 237
WOR-C121A 38
548 593 469 402 292 533 212 322 485 482 423 650 308 298 347 519 320 178 234 376
338 242 293 285 298 458 437 293 223 180 259 230 309 312 381 285 174 234
WOR-C121B 38
545 611 484 378 296 553 229 323 450 441 427 614 303 280 371 488 311 156 231 377
345 244 286 283 296 452 418 298 224 179 261 224 319 308 387 286 163 285
WOR-C122A 67
280 138 109 154 228 259 240 212 310 260 227 350 349 432 314 310 180 243 216 233
159 149 115 130 240 197 195 154 207 169 158 127 118 94 72 67 71 90 87 95
62 162 149 112 105 113 149 273 187 109 117 129 89 73 79 85 73 112 71 105
190 187 242 112 191 165 171
WOR-C122B 67
273 132 110 156 221 288 238 211 320 264 233 345 361 457 308 306 181 250 205 231
139 119 119 132 252 205 203 159 235 206 152 136 115 92 71 67 67 78 88 103
63 143 151 108 105 113 151 279 185 101 120 130 92 74 76 88 76 130 84 102
207 172 239 121 187 164 174
WOR-C123A 48
192 231 183 202 180 220 302 192 164 189 208 276 234 235 266 152 155 102 157 157
206 152 162 174 159 206 178 255 200 176 175 169 161 179 131 156 140 191 197 182
207 252 266 205 173 186 193 264
WOR-C123B 48
204 245 174 199 184 219 311 193 165 190 217 270 232 245 236 148 156 105 160 160
206 138 166 204 177 221 186 245 195 170 179 156 191 191 137 150 135 210 216 216
186 231 263 224 172 190 177 296
WOR-C124A 98
248 237 230 160 109 69 78 97 123 140 153 125 85 88 53 45 58 77 67 63
58 58 60 110 286 198 161 154 171 143 87 105 107 82 70 63 85 223 283 204
103 108 127 190 220 170 138 167 222 157 175 132 132 123 183 234 189 238 210 105
127 66 128 165 125 150 167 159 123 79 74 109 115 137 103 101 60 50 114 94
93 80 101 88 54 48 65 58 57 74 67 58 66 50 66 76 75 64
WOR-C124B 98
349 207 246 143 88 82 86 103 113 142 155 125 83 86 53 38 62 74 65 62
54 57 56 114 303 196 161 139 153 152 89 103 108 89 66 60 86 226 239 211
159 94 122 176 221 171 119 144 185 161 181 130 141 109 172 226 180 230 215 113
136 68 125 143 123 161 181 155 121 76 83 103 114 148 92 101 58 49 100 95
93 83 100 84 56 46 64 54 74 70 73 61 58 57 61 71 60 81
WOR-C125A 114
240 192 134 98 116 163 171 222 187 171 177 306 389 197 175 170 223 179 196 106
157 143 89 86 118 221 264 196 95 95 117 128 209 192 161 189 173 91 127 106
130 118 166 195 250 286 270 120 147 77 108 145 111 135 199 182 172 90 80 138
193 203 133 134 81 57 131 142 120 123 196 136 75 62 87 91 75 83 71 75
73 65 80 146 165 145 184 167 264 142 149 113 122 118 62 96 90 115 79 74
100 122 94 168 149 145 123 94 104 100 112 147 154 192

WOR-C125B 114
230 196 132 94 124 169 167 232 183 170 175 297 380 201 178 169 225 175 182 128
173 152 96 89 113 201 247 215 94 102 132 118 202 187 158 189 176 98 120 108
122 122 165 192 258 287 260 132 141 83 107 151 116 131 190 181 163 88 83 131
182 215 141 143 79 63 137 142 115 129 202 137 72 71 96 84 80 68 82 80
62 68 73 149 151 146 177 165 290 141 148 106 122 113 64 92 104 112 90 69
96 131 95 159 152 149 130 92 98 109 110 150 154 185
WOR-C126A 86
486 322 310 324 264 191 229 323 427 402 340 334 261 290 291 256 261 285 347 332
298 262 236 191 125 90 77 85 106 125 83 121 143 234 230 254 162 158 128 95
76 83 69 63 65 50 45 60 56 48 73 70 63 64 102 114 105 137 145 92
120 144 300 202 206 156 195 194 151 135 129 114 243 205 133 163 166 136 133 126
154 166 98 114 167 156
WOR-C126B 86
552 330 309 309 267 188 218 329 425 401 334 323 269 287 295 253 257 294 352 331
301 273 235 199 130 94 76 78 104 124 88 117 144 245 226 244 164 145 114 94
75 81 65 68 65 54 41 58 61 51 73 66 63 64 114 104 117 122 150 96
111 151 305 177 209 161 189 195 151 135 140 118 249 198 129 169 152 148 116 139
156 168 103 108 161 177
WOR-C127A 49
276 332 476 242 218 154 162 143 112 143 229 286 241 364 327 400 231 192 271 285
360 456 600 368 348 337 409 278 288 291 227 381 240 179 235 288 232 210 185 231
216 279 310 296 252 256 210 266 321
WOR-C127B 49
311 349 445 249 202 168 155 143 113 150 263 295 248 366 308 429 255 199 254 291
367 455 594 354 344 326 398 269 301 288 222 376 234 190 236 282 227 208 189 227
221 270 318 310 239 263 214 263 323
WOR-C128A 63
476 387 308 263 252 256 211 196 247 271 306 204 200 220 166 228 173 193 143 175
177 175 172 209 96 202 201 288 271 217 271 258 398 235 185 288 228 224 187 284
263 261 224 205 286 244 231 160 169 173 151 163 132 185 186 164 151 133 171 152
147 174 200
WOR-C128B 63
520 375 294 250 310 247 201 180 225 249 293 208 196 225 184 234 172 183 134 165
182 167 179 164 90 206 205 262 289 190 264 258 403 232 203 272 223 221 193 296
252 250 202 215 278 241 236 160 166 160 149 159 139 191 185 164 128 152 169 156
140 215 213
WOR-C129A 54
410 373 292 342 353 474 281 428 382 334 468 360 251 502 394 453 396 382 335 455
363 270 329 352 319 282 229 314 211 266 209 402 362 308 323 180 158 171 121 160
112 155 235 169 112 186 160 124 110 86 155 177 263 200
WOR-C129B 54
358 361 310 331 342 463 285 433 403 315 456 374 247 498 397 443 402 375 344 450
373 260 324 352 334 268 219 323 208 264 212 406 367 328 318 175 154 189 113 152
115 150 230 167 118 187 163 135 96 103 174 151 260 200
WOR-C130A 45
354 443 398 241 471 454 480 483 323 257 313 433 331 278 342 248 304 297 271 263
290 280 349 460 392 398 333 235 257 242 219 170 190 307 281 288 324 272 235 202
163 229 211 254 198

WOR-C130B 45
443 417 395 233 463 469 492 474 340 255 334 423 313 305 400 273 281 298 255 256
273 296 375 463 388 410 333 229 249 238 222 170 186 319 270 324 338 310 238 192
151 259 205 290 210
WOR-C131A 38
397 457 403 443 474 567 575 568 558 465 452 501 452 421 368 493 454 465 525 360
276 438 346 395 292 385 436 270 240 304 279 178 209 226 333 351 390 300
WOR-C131B 38
403 445 416 447 460 566 583 564 562 486 464 506 440 433 364 512 454 460 517 347
258 455 351 400 303 372 433 276 244 297 279 172 204 207 410 332 370 300
WOR-C132A 45
396 620 518 269 586 428 500 510 403 423 462 420 161 156 243 231 275 336 357 304
235 240 428 411 390 381 328 235 324 259 288 249 269 256 150 155 150 204 141 192
182 360 208 250 200
WOR-C132B 45
396 606 525 270 566 447 496 514 386 431 457 414 189 209 235 214 259 331 345 263
228 252 379 402 388 377 335 270 331 190 316 237 275 261 157 147 169 201 141 179
176 359 202 258 197
WOR-C133A 54
198 238 443 379 386 308 265 238 260 300 293 319 412 359 326 341 214 381 415 371
404 311 272 312 335 266 272 268 268 302 264 170 153 247 320 417 349 333 343 224
385 405 400 406 290 284 321 322 285 249 252 278 286 236
WOR-C133B 54
228 247 474 399 382 287 258 223 276 300 293 326 406 358 333 339 224 385 345 374
423 305 286 334 324 276 263 252 272 287 222 190 142 200 337 405 370 349 333 216
347 345 398 403 308 288 305 329 260 282 256 281 274 244
WOR-C134A 48
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342 282 311 337 359 373 448 309 269 295 253 349 374 208 227 256 229 385 465 716
531 641 351 485 351 460 399 430
WOR-C134B 48
343 675 460 448 441 557 604 567 690 555 524 416 408 383 627 436 440 502 409 427
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528 632 353 450 380 437 400 399
WOR-C135A 54
544 603 695 524 611 527 624 689 602 642 552 555 605 693 519 625 668 619 485 326
522 534 417 555 489 512 409 276 271 263 191 222 343 306 337 301 270 272 210 221
285 308 280 274 302 249 331 296 123 165 300 222 477 376
WOR-C135B 54
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538 510 409 569 471 481 411 275 253 263 196 211 337 290 359 291 278 258 205 212
290 307 303 276 307 258 337 308 118 178 277 220 445 379
WOR-C136A 56
461 511 426 372 319 305 227 214 228 215 221 336 269 359 296 360 300 249 192 278
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301 250 224 230 184 263 208 135 127 226 266 380 350 483 388 480
WOR-C136B 56
457 502 436 372 307 315 206 214 239 218 233 333 300 382 304 352 285 252 159 300
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293 239 235 221 195 247 222 118 142 232 231 400 350 468 381 494

WOR-C137A 57
423 477 448 403 501 396 369 386 477 548 477 555 472 459 261 311 337 303 422 307
424 333 234 226 238 171 176 268 285 360 324 268 219 174 225 297 310 236 232 239
195 259 224 134 148 244 200 384 384 487 421 498 282 324 272 312 297
WOR-C137B 57
444 461 432 403 462 403 383 393 467 511 426 586 503 481 268 361 354 385 410 339
392 324 206 208 217 183 187 301 294 370 324 270 219 172 231 283 311 228 237 254
187 242 224 136 141 233 202 375 385 506 433 486 295 322 250 316 255
WOR-C138A 61
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281 227 262 208 219 307 263 327 268 278 271 189 242 299 314 223 250 234 212 222
205 134 125 218 229 361 393 502 403 505 253 288 213 324 308 284 186 219 250 238
248
WOR-C138B 61
246 323 338 370 399 429 439 445 410 424 348 342 200 275 324 272 346 299 311 302
279 230 264 200 222 324 273 332 283 273 227 197 230 281 315 250 242 232 224 227
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297
WOR-C139A 61
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205 130 144 219 220 357 388 511 395 495 262 289 222 348 304 297 187 217 252 221
250
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135 101 139 132 145 105 113 79 96 102 91 127 98 85 65 69 80 97 72 96
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WOR-C142A 80
235 207 361 183 160 288 247 209 194 260 231 187 240 173 148 187 216 200 211 213
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117 105 76 121 107 95 125 105 79 65 71 100 96 79 84 83 82 87 118 132
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152 121 143 93 116 104 139 110 104 88 88 115 98 101 94 81 118 104 135 136
130 123 97 125 109 135 127 97 95 160 133 114 172 127 162 156 127 146 118 79
109 111 100 141 91 134
WOR-C143B 66
187 162 283 340 332 211 312 292 227 299 203 139 247 269 211 225 237 176 165 173
169 118 145 116 112 104 138 101 107 94 92 106 92 111 96 82 112 99 124 145
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100 116 102 133 122 152

Figure 4a: Plan showing the positions of the core samples from the structural timbers of St John Chapel roof

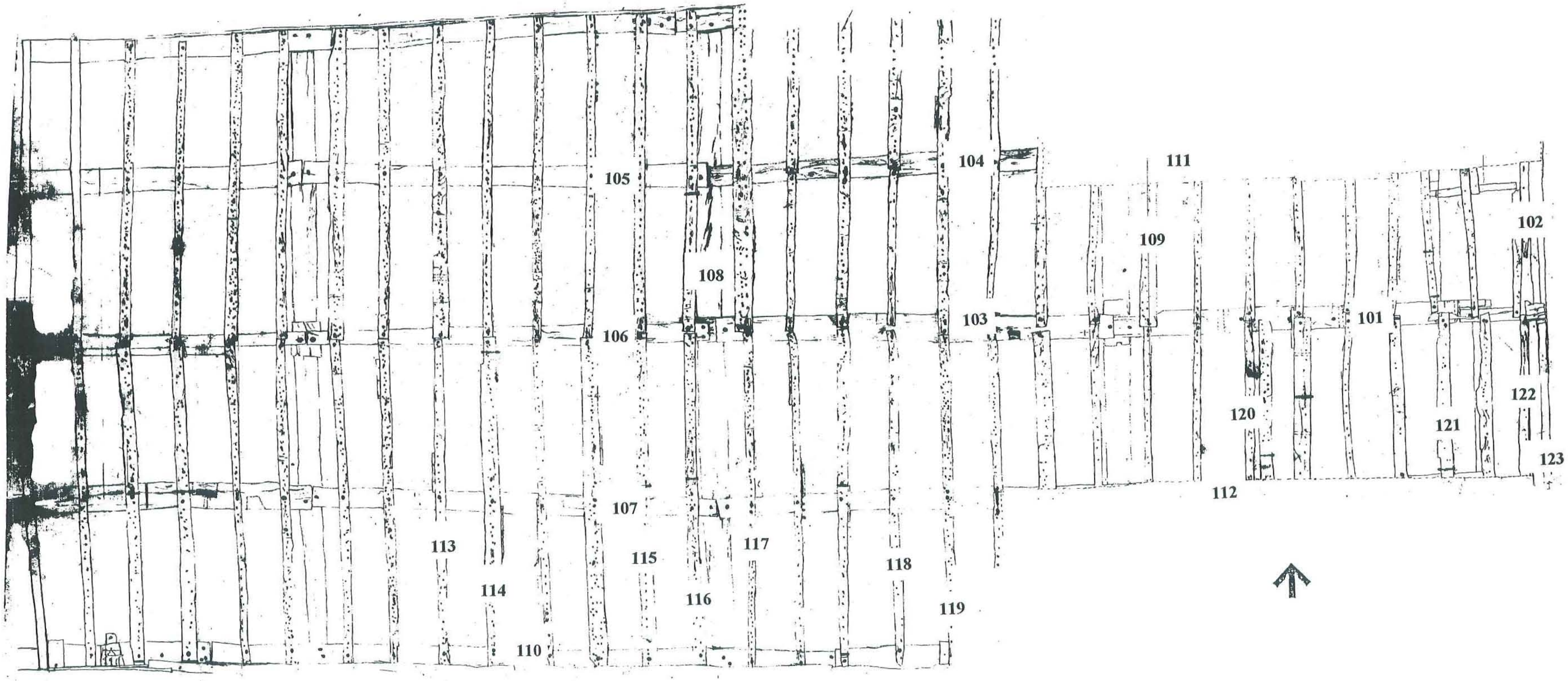
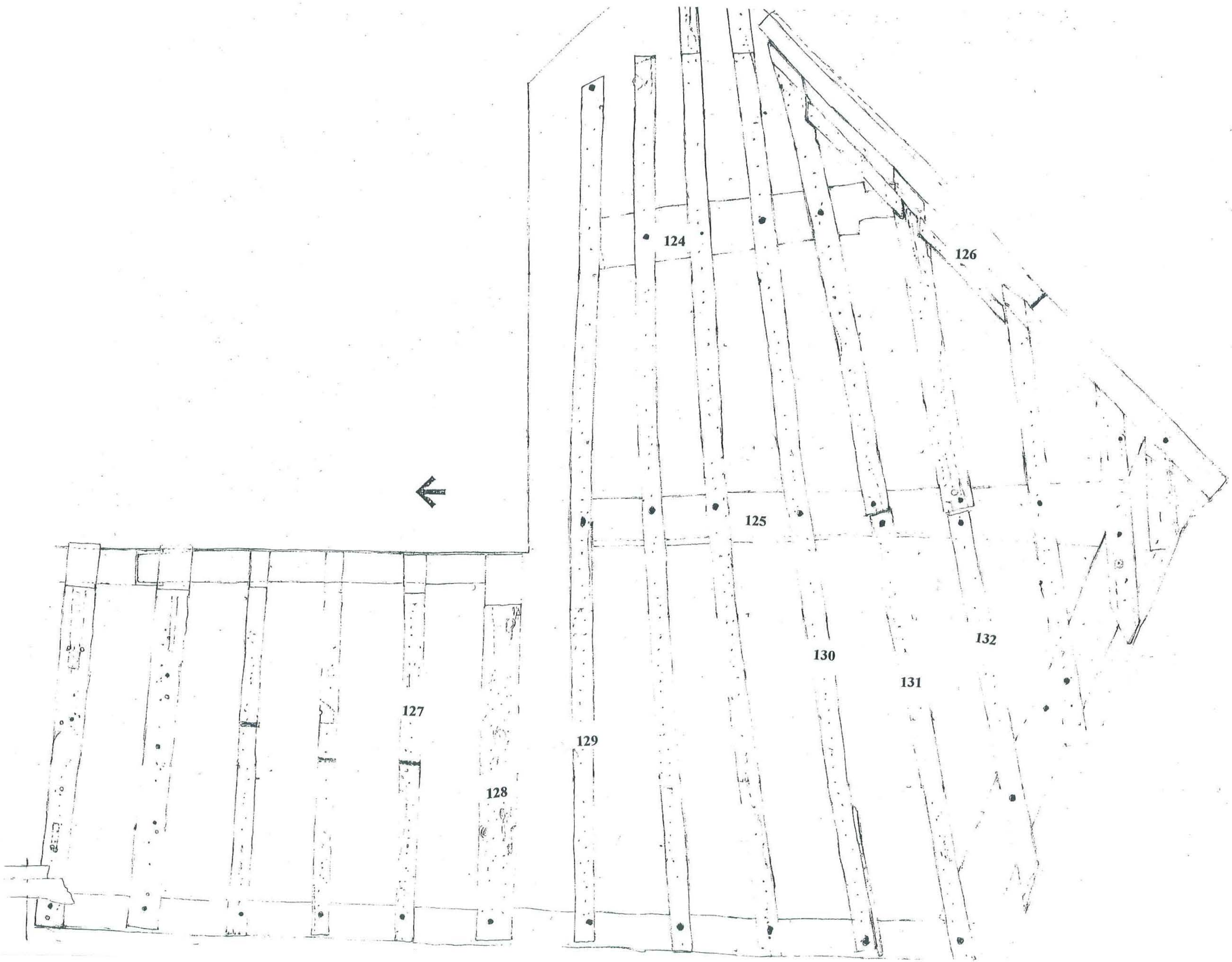


Figure 4b: Plan showing the positions of the core samples from the structural timbers of the connecting roof



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 Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). 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 Figure1 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, 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 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. 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 we inspect the timbers in a building 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. Similarly the core has just over 100 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.

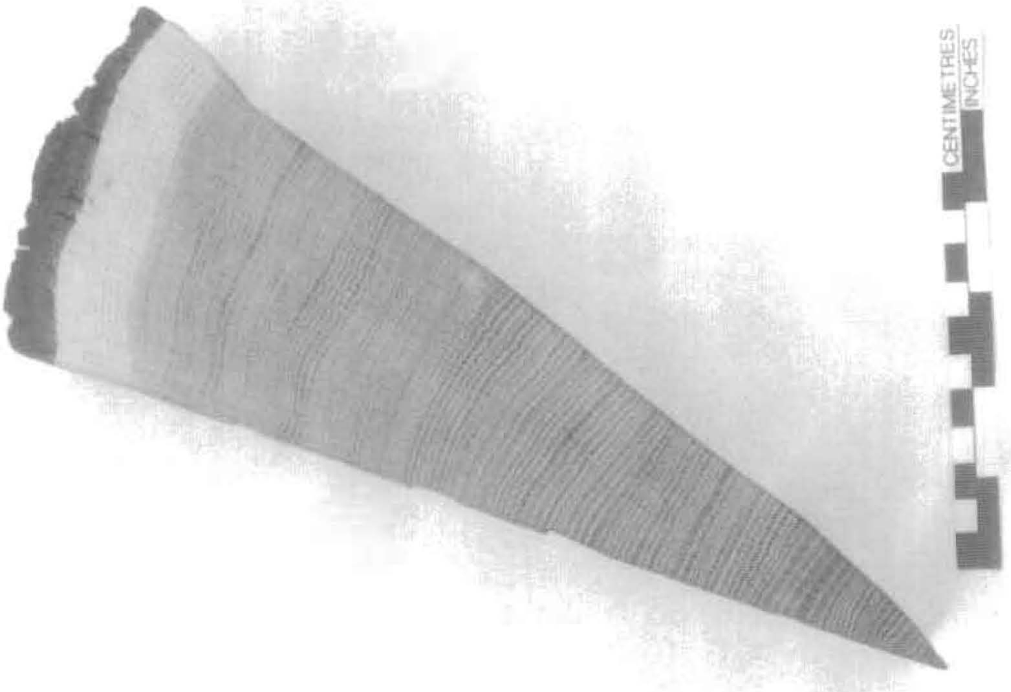


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

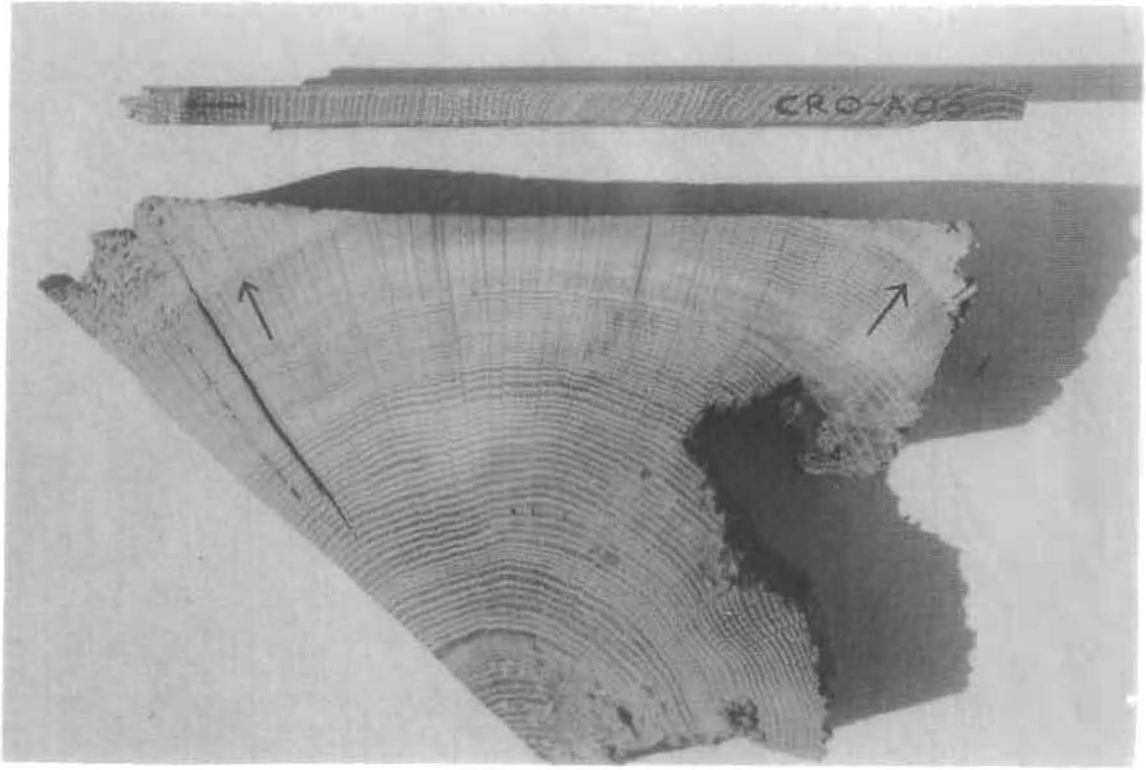


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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 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.

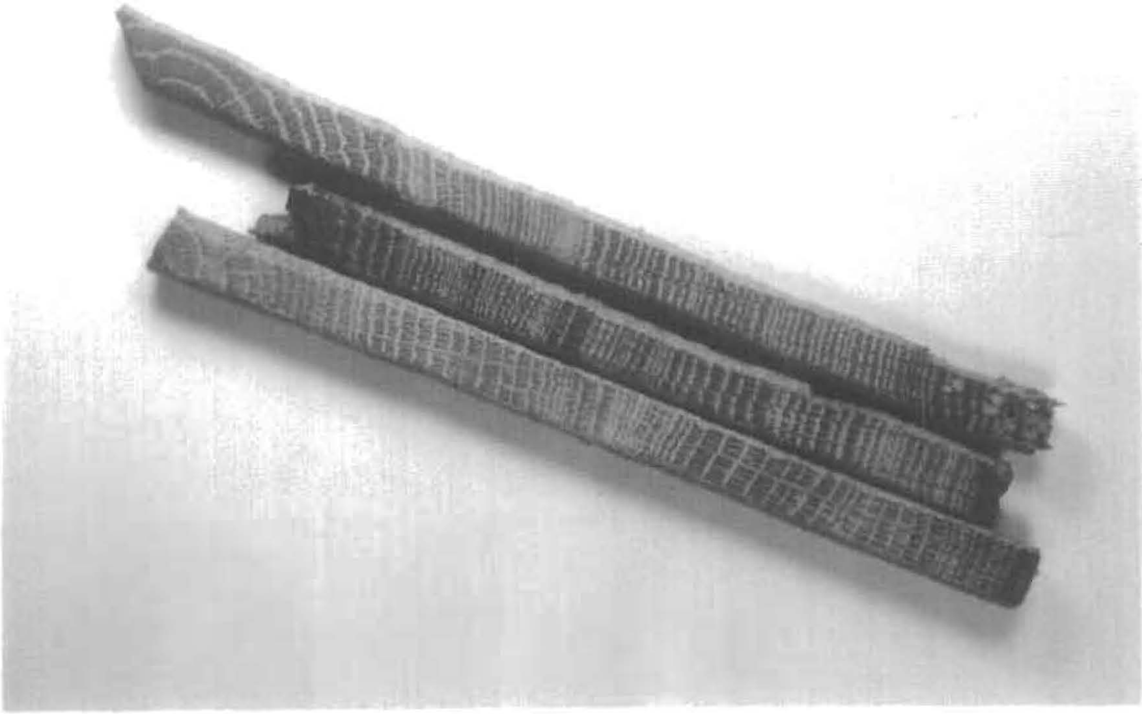


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 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 inspecton 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 is insured with the CBA.

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 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; 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. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45. 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 between these two whatever the position of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the 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 from 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. 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.

average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

This 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'. This was developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988a). To illustrate the difference between the two approaches with the above example, consider sequences C08 and C05. They are the most similar pair with a t-value of 10.4. Therefore, these two are first averaged with the first ring of C05 at +17 rings relative to C08 (the offset at which they match each other). This average sequence is then used in place of the individual sequences C08 and C05. The cross-matching continues in this way gradually building up averages at each stage eventually to form the site sequence.

4. ***Estimating the Felling Date.*** 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, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. 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 for 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. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

   Various estimates have been made for the average number of sapwood rings in a mature oak. One estimate is 30 rings, based on data from living oaks. So, in the case of the core in Figure 2 where 9 sapwood rings remain, this would give an estimate for the felling date of 21 (= 30 - 9) years later than of the date of the last ring on the core. Actually, it is better in these situations to give an estimated range for the felling date. Another estimate is that in 95% of mature oaks there are between 15 and 50 sapwood rings. So in this example this would mean that the felling took place between 6 (= 15 - 9) and 41 (= 50 - 9) years after the date of the last ring on the core and is expected to be right in at least 95% of the cases (Hughes *et al* 1981; see also Hillam *et al* 1987).

   Data from the Laboratory has shown that when sequences are considered together in groups, rather than separately, the estimates for the number of sapwood can be put at between 15 and 40 rings in 95% of the cases with the expected number being 25 rings. We would use these estimates, for example, in calculating the range for the common felling date of the four sequences from Lincoln Cathedral using the average position of the heartwood/sapwood boundary (Fig 5). These new estimates are now used by us in all our publications except for timbers from Kent and Nottinghamshire where 25 and between 15 to 35 sapwood rings, respectively, is used instead (Pearson 1995).

   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. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, 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 40 years later we would have estimated without this observation.

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

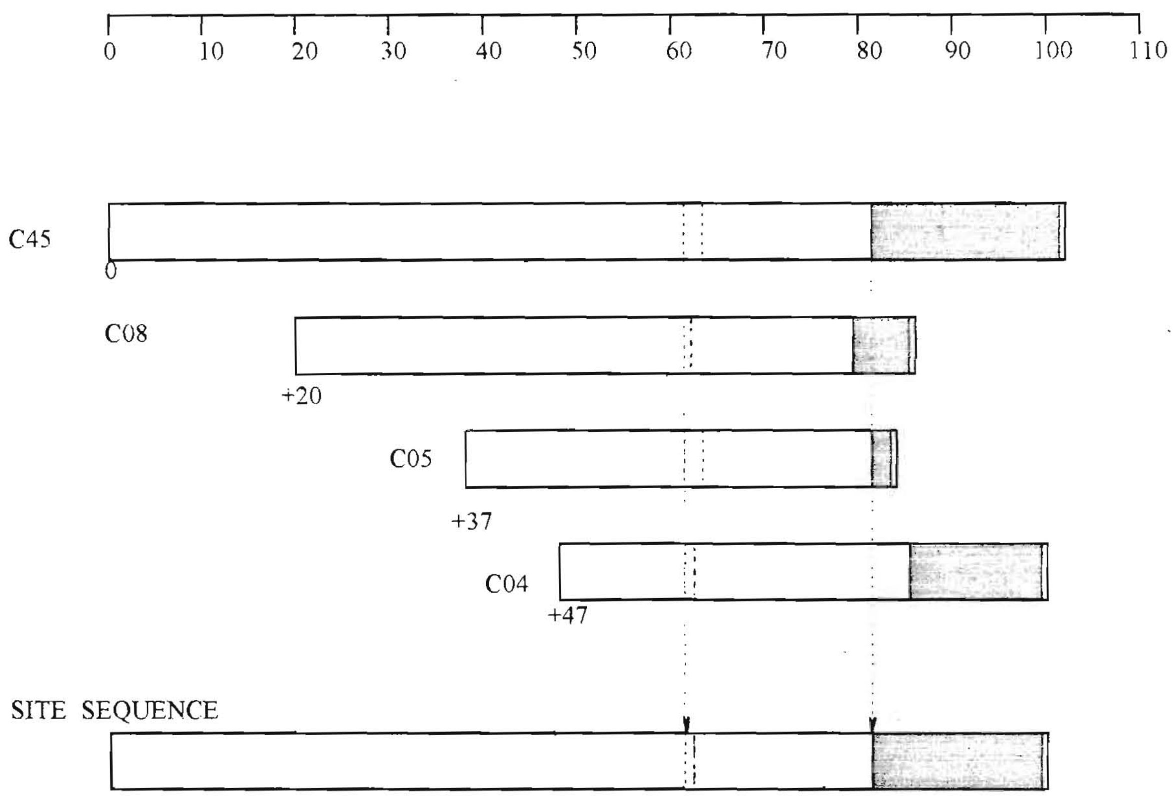


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set 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.

Even if all the sapwood rings are missing on all the timbers sampled, an estimate of the felling date is still possible in certain cases. For provided the original last heartwood ring of the tree, called the heartwood/sapwood boundary (H/S), is still on some of the samples, an estimate for the felling date of the group of trees can be obtained by adding on the full 25 years, or 15 to 40 for the range of felling dates.

If none of the timbers have their heartwood/sapwood boundaries, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ,* and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed 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 1988b, 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* 1988a). 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 (1988b) 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 (a), the generally large early growth after 1810 is very apparent as is the smaller generally later growth from about 1900 onwards. A similar difference can be observed in the lower sequence 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, hopefully corresponding to good and poor growing seasons, respectively. The two corresponding sequences of Baillie-Pilcher indices are plotted in (b) where the differences in the early and late growths have been removed and only the rapidly changing peaks and troughs remain only associated with the common climatic signal and so make cross-matching easier.

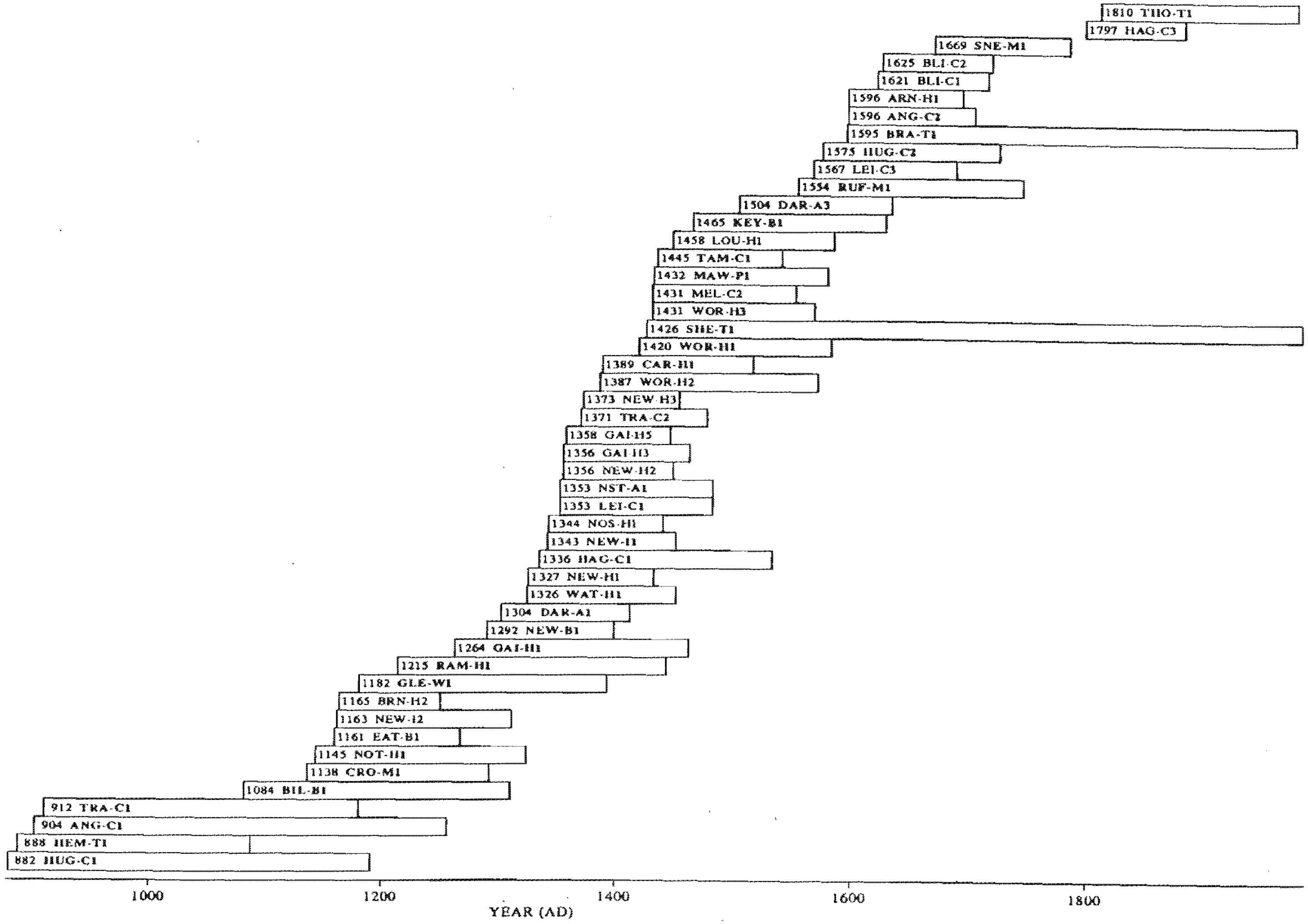


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

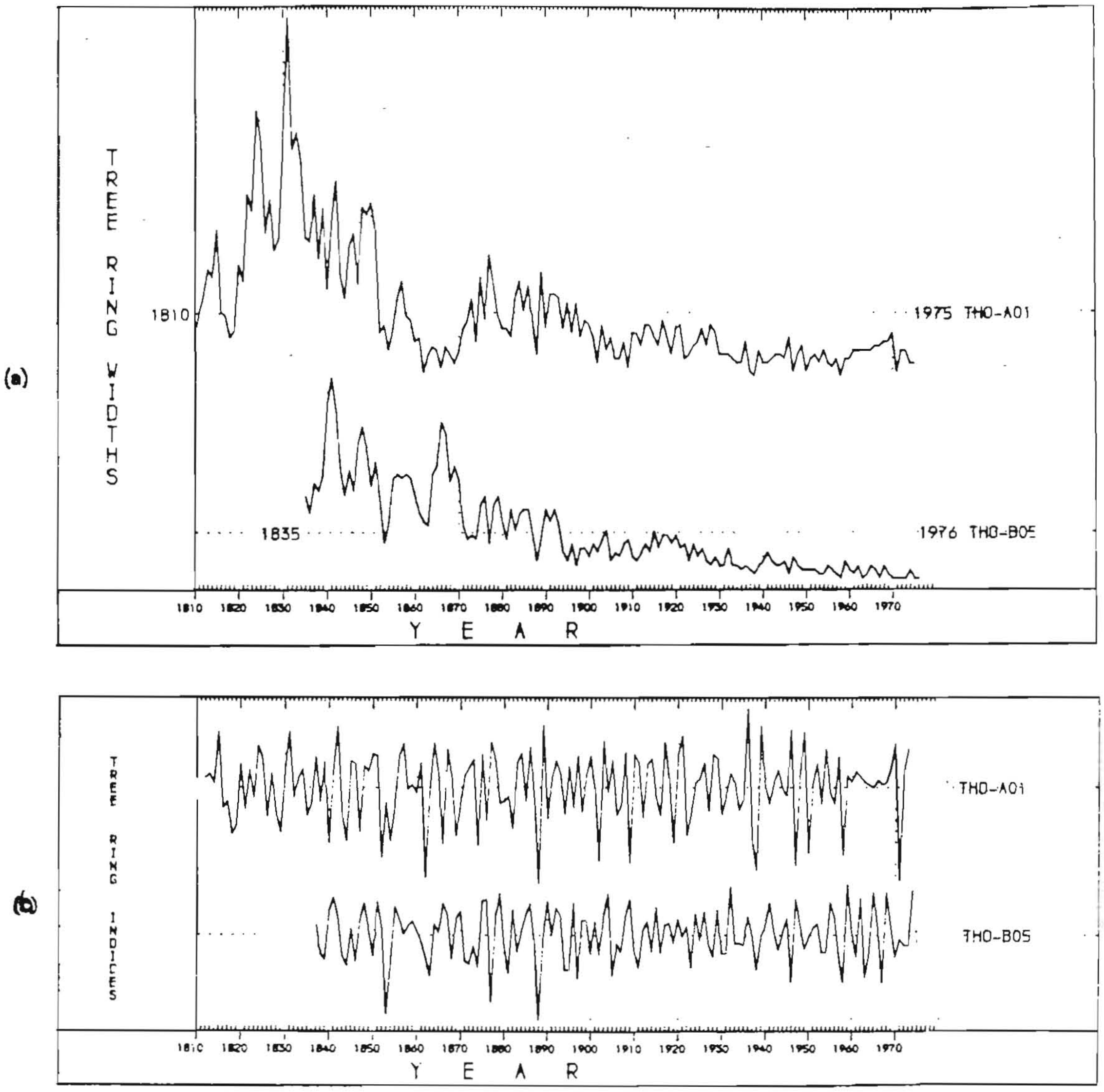


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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