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POLESWORTH ABBEY GATEHOUSE, POLESWORTH, WARWICKSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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Summary

Analysis by dendrochronology of 39 out of 44 samples obtained from this site has produced two dated site chronologies and dated one sample individually.

The first site chronology, POLCSQ01, comprises 21 samples, all from the roof, walls, and floor-frame of the eastern part of the building (the Gatehouse proper), as well as from the floor of the mezzanine room here. This site chronology has 248 rings, dated as spanning AD 1095–1342.

The second site chronology, POLCSQ02, comprises 11 samples, all from the roof of the west part of the building (the 'annex') and its southern arm. This site chronology has 137 rings, dated as spanning AD 1446–1582. A single sample from the annex roof was dated individually as spanning AD 1361–1487.

Analysis by tree-ring dating has demonstrated that two distinct periods of felling are represented. All the structural timbers of the Gatehouse proper, and the majority of timbers from the mezzanine floor here, were probably felled in the latter half of the AD 1330s and the early AD 1340s.

The roof timbers of the annex roof, and its south arm, were probably all felled in AD 1582.

Keywords

Dendrochronology
Standing Building

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Introduction

Polesworth Abbey, originally a Benedictine foundation, and the core of the medieval village, is set on the north bank of the River Anker, approximately 2km north of the A5 trunk road in Warwickshire (SK 262 025, Figs 1 and 2). The Abbey Gatehouse itself is situated on the northern perimeter of the abbey precinct, close to the church of St Editha and adjacent to the High Street, which leads east towards Warton and Orton-on-the-Hill. It stands in the Polesworth Conservation Area and forms part of a Scheduled Ancient Monument. The Gatehouse is also on the English Heritage register of Buildings at Risk. It has recently been the subject of a full and extensive architectural and archaeological survey, from which much of the introductory description given here is taken (Alcock *et al* 2007).

The Gatehouse proper

The Gatehouse structure is in two distinct parts (Fig 3). The first or eastern part is Grade II* listed and comprises the main carriageway opening and the adjacent pedestrian portal; it is believed to have been constructed in the fourteenth century, with stone to the ground floor and a mainly timber-framed upper floor. Sometimes referred to locally as 'the dungeon', a small, low room to the east of the pedestrian portal is interpreted as a gatekeeper's lodge. A primary doorway near the south-east corner of the building (to the rear) gives access to stairs which lead up to the room at mezzanine level over the gatekeeper's lodge, this room having a split floor-level as it steps up over the pedestrian portal.

The stairs then climb to the first floor, giving access to a three-bay single-aisled structure with a crown-post roof comprising three trusses (A, B, and C; Fig 4a). One of the trusses, truss C/CC, was originally a closed partition, so the first floor originally comprised a two-room unit of accommodation, linked by a doorway through the partition. Bays I and II, over the pedestrian portal and the gatekeeper's lodge, contained the larger, superior, room, while bay III, above the carriageway opening, contained a smaller single-bay chamber. The larger two-bay room had direct access from inside the abbey precinct via the stairs under the aisle roof; it also had a source of heat and a latrine. The smaller unheated room in bay III was less private. In addition to the doorway from bay II, a primary doorway with a two-centred arch connected it with the west end of the building (the portion of the structure that was rebuilt after the Dissolution).

Two bays of the aisle off the south side of the main chamber were partitioned into small compartments; one of them contained the stairs in their original form, and the other is interpreted as a garderobe or latrine. One of the prime duties of medieval monastic houses was hospitality, whether for patrons or visitors of various ranks, so these rooms might have been part of a lodging range. However, a variety of accommodation was also required for lay officers, and sometimes for priests.

The 'annex' and south arm

Adjoining the west end of the Gatehouse proper, having a slightly different roof line, but likewise running parallel to the road, is the second or western part of the Gatehouse structure, which includes a single-bay gabled arm to its south. This portion is listed Grade II. Given that little of its original medieval plan form or other lower internal features either survive or are presently visible (there are certainly no lower timbers currently to be seen) it is difficult to determine what function this part of the building might have had. In view of this uncertainty the building is simply referred to as the 'annex'. The southern arm might have been a porch or a stairway.

The annex has a three-bay roof structure, supported by four trusses (D, E, F, and G; Fig 4b) and double side purlins. The trusses comprise tiebeams, a single collar, and two substantial principals, tapered at the top. Although in some cases now lost, all the trusses had three struts between tiebeams and collars. There are stave sockets in the collar and principals, and a groove on the top face of the tiebeam, of truss D (abutting the west wall of the Gatehouse proper) indicating that this was intended as a closed truss. The struts and the panel infill have all been removed, probably when an aperture was broken through the stone wall behind the truss.

Although the evidence obtained so far is contradictory, the stone bay projecting from the west end of the annex south wall is tentatively interpreted as either a storeyed porch or a stair turret. There are two roof-trusses over the south arm. If there are tiebeams they are hidden between floor and ceiling, but over such a narrow building it is possible that the trusses are comprised of just the principals and a collar. Unlike the threaded purlins in the main roof, those over the south arm are clasped between the principals and the collars At the gable apex (unseen at the time of tree-ring sampling) there is a finial bearing three dates, the earliest of which is AD 1583. A schematic plan of the building is given in Figure 5**.**

The architectural evidence for the age of the building

Architectural and archaeological analysis of the historic fabric of the Polesworth Gatehouse has identified a range of structural and stylistic techniques and characteristics which can be compared with other buildings of known date. Masonry details include shouldered arches on two windows and a fireplace, and two-centred arches with quarter-round mouldings or chamfers on doorways, both plausible indicators of a date in the second quarter of the fourteenth century.

The timber frame is a remarkable survival which, on typological evidence, should, like the masonry, date from the second quarter of the fourteenth century. Crown-post roofs are now rare in the immediate vicinity, but 186-7 Horninglow St, Burton-on-Trent, Staffordshire, provides just one example, tree-ring dated to AD 1345 (Howard *et al* 1995). The Polesworth crown-post retains one interesting early characteristic – the upward braces are halved across the collars then morticed into the soffits of the rafters. The arcade framing includes upward and downward cusped braces, and the deep, curved arch-braces in each of the transverse trusses A-C are also cusped. Cusping continued in use in the area until the 1440s – as on the wind-braces in the open hall in Tamworth Castle, but that is a post-and-truss structure with a tiebeam and double collar roof, a rather later style of building. Nevertheless, the crown-post roof at Mavesyn Ridware Gatehouse, Staffordshire, has been tree-ring dated to AD 1391 (Howard *et al* 1996a).

The mezzanine floor (the ceiling of the gatekeeper's lodge) was constructed using at least some timber reused from an older building. One of the joists retains one notched lap-joint and a halving. Presumably, as these timbers are an integral part of the structure, they were reused in the fourteenth century from a dismantled older structure, potentially from within the abbey precinct.

The Gatehouse is therefore part of a small but significant group of medieval crown-post roof buildings in the west midlands.

Sampling

Sampling and analysis by tree-ring dating of timbers within both parts of the Gatehouse were commissioned by English Heritage, the analysis of material from five distinct areas of the structure being requested. Primary amongst these were the timbers forming the roof, wall, and floor frames of the eastern portion of the building, the Gatehouse proper, this section believed to be the earlier part of the present building. On the basis of the survey recently undertaken it was believed that all these timbers represented a single phase of construction.

Secondly, sampling of the timbers forming the ceiling of the gatekeeper's lodge (the floor of the mezzanine chamber) was also requested. The date of these timbers was uncertain, and there was clear evidence that some of the timbers were reused, possibly, it was believed, from another earlier structure in the abbey precinct.

Tree-ring samples were also requested from two areas of the annex, the roof covering the main body and from the roof of the small single-bay arm to the south. In this western portion of the building there were no other timbers visible in the lower walls, floors, or ceilings.

Finally, the English Heritage brief requested that samples be obtained from the beams forming the ceiling of the carriageway opening.

The purpose of this programme of tree-ring analysis was to inform a programme of grant-aided repairs. It was hoped that analysis would confirm the date of the main body of the eastern portion, the dates of the timbers in the ceiling of the gatekeeper's lodge, and determine the date for the western portion of the building as well, establishing whether or not the porch structure is the same date as the roof of this half.

From the material available a total of 44 samples was obtained by coring from four of the areas required, each sample being given the code POL-C (for Polesworth, site 'A'). Due to the intermittent nature of access to the site, with different parts of the building becoming available for sampling at different times, it was felt advisable to leave gaps between some of the sample numbers. This was done in case it became necessary to core additional timbers from any particular, previously sampled, part of the building. Some of the sample numbers, therefore, do not run consecutively.

Thus, 10 samples, POL-C01–10, were obtained from the annex roof, all the sampled timbers appearing to be primary and integral to the structure. Although there are some other timbers available here, they appear to be derived from relatively fast-grown trees and are thus likely to have fewer rings. Sixteen samples, POL-C11–26, were then obtained from the roof, wall, and floor-frames of the Gatehouse proper, with all sampled timbers again appearing to be primary and integral. A further 11 samples, POL-C31–41, were obtained from the mezzanine floor; one of these timbers, as indicated above, showed evidence of reuse. Finally, seven samples, POL-C51–57, were obtained from the relatively small roof of the south arm of the annex, the timbers once more all appearing to be primary.

No samples were obtained from any of the nine beams forming the ceiling of the carriageway opening. Few of the beams were consistent enough in size or form to suggest they represented a coeval group. Some appeared to show very regular mechanical saw marks, suggesting they were relatively modern, perhaps twentieth-century, while two appeared to be of very modern softwood. Other ceiling beams, although of oak and possibly of some antiquity, were derived from very fast-grown trees, and as such were unlikely to provide satisfactory samples.

Where possible (the exceptions being samples POL-C53–57), the positions of these samples are marked on plans made and provided by Jean and Bob Meeson as part of the survey report. These are reproduced here as Figures 6a–i. Details of the samples are given in Table 1. In this Table, the bays, trusses, and other timbers have been located and numbered following the schema on the drawings provided.

The Laboratory would like to take this opportunity to thank Father Philip Wells, for his enthusiasm for this programme of tree-ring analysis and for taking a keen interest in proceedings. We would also like to thank Nat Alcock, and Jean and Bob Meeson for the use of their drawings, and large portions of text from their survey of the building, used in the introduction above.

Analysis

Each of the 44 samples obtained was prepared by sanding and polishing. It was seen at this point that five samples had too few rings for reliable dating, ie, less than 54, and these were rejected from this programme of analysis. The annual growth-rings of the remaining 39 samples were measured, however, the data of these measurements being given at the end of this report. The data of these 39 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see appendix), allowing two groups of cross-matching samples to be formed as shown in the bar diagrams, Figures 7 and 8. The samples of the two groups were combined at their indicated off-sets to form site chronologies POLCSQ01 and POLCSQ02 respectively.

The first site chronology, POLCSQ01, comprises 21 samples, with an overall length of 248 rings. This site chronology was compared to a number of relevant reference chronologies for oak, this indicating a consistent cross-match with a large number of these when the date of the first ring is AD 1095 and the date of the last ring is AD 1342. Evidence for this dating is given in the *t*-values of Table 2.

The second site chronology, POLCSQ02, comprises 11 samples, with an overall length of 137 rings. Site chronology POLCSQ02 was also compared to a number of relevant reference chronologies for oak. This again indicated a consistent cross-match when the date of the first ring is AD 1446 and the date of the last ring is AD 1582. Evidence for this dating is given in the *t*-values of Table 3.

Both site chronologies were compared with the seven remaining measured but ungrouped samples but there was no further satisfactory cross-matching. Each of the seven samples was then compared individually with a full range of reference chronologies for oak. This indicated a cross-match for one further sample, POL-C07, when the date of its first ring is AD 1361 and the date of its last ring is AD 1487. Evidence for this dating is given in the *t*-values of Table 4.

Interpretation

Analysis by dendrochronology of 39 measured samples from this site has produced two dated site chronologies and dated one sample individually.

The first site chronology, POLCSQ01, comprises 21 samples, all from the roof, walls, and floor frame of the east part of the building, the Gatehouse proper, and from the floor of the mezzanine room (the ceiling of the gatekeeper’s lodge). This site chronology has a first ring date of AD 1095 and a last ring date of AD 1342. Three samples in this site chronology, POL-C26, from the floor frame of the Gatehouse proper, and samples POL-C35 and C40 from beams of the mezzanine floor, all retain complete sapwood. This means that they each have the last ring produced by the trees represented before they were felled.

In the case of sample POL-C35 the last measured, complete, sapwood ring is dated to AD 1336. The last complete sapwood ring on sample POL-C40 is slightly later at AD 1339, whilst the last complete sapwood ring on sample POL-C26 is dated AD 1342. These are thus the felling dates of the trees represented. The relative position of the heartwood/sapwood boundary, where it exists, on the other 13 dated samples in site chronology POLCSQ01 is highly indicative of a group of timbers representing a common felling period having very similar, if not in this case actually identical felling dates. All dated timbers from the Gatehouse proper therefore appear to have been felled in the latter half of the AD 1330s or the early AD 1340s.

The second site chronology, POLCSQ02, comprises 11 samples, all from the roof of the annex and its south, single-bay, arm. This site chronology has a first ring date of AD 1446 and a last ring date of AD 1582. Five of the samples in this site chronology, POL-C01, C02, C04, and C08, from the annex roof, and sample POL-C51, from the south arm, again retain complete sapwood. In all five examples the last measured, complete, sapwood ring is dated to AD 1582. This is thus the felling date of the trees represented. The relative position of the heartwood/sapwood boundary, where it exists, on the other four dated samples in site chronology POLCSQ02 is indicative of these timbers having been felled in AD 1582 as well.

The timber, the collar of truss E in the annex roof, dated by the individual sample, POL-C07 (last ring date AD 1487), does not retain any sapwood or, indeed, the heartwood/sapwood boundary. It is thus not possible to indicate its likely felling date. While it is possible that this timber was felled earlier than the other timbers in this roof, though probably not before AD 1502 (this figure based on a 95% probability of a minimum of 15 sapwood rings), there is no indication, by way of redundant mortice or peg holes, that this timber has been reused and there is no structural evidence to suggest that it was not felled in AD 1582 also. It therefore seems likely that POL-C07 represents the inner part of a long-lived tree that was heavily trimmed during conversion.

Conclusion and discussion

Analysis by tree-ring dating has demonstrated, therefore, that two distinct periods of felling are represented in the Gatehouse of Polesworth abbey, this reflecting the two distinct parts discerned in the architectural survey. As suggested in this survey, the Gatehouse proper, the eastern part of the building, dates to the second quarter of the fourteenth century, with tree-ring dating showing that all the main structural timbers were felled during the latter half of the AD 1330s and the early AD 1340s. Unexpectedly perhaps, this includes the majority of timbers from the floor of the mezzanine room (the roof of the gatekeeper's lodge), which were previously believed might be reused from an older building. One timber from this mezzanine floor which shows clear evidence, by way of a notched lap-joint halving, of reuse, represented by sample POL-C37, remains undated, and it remains a possibility that this is an older piece.

Judging by the degree of cross-matching between some of the samples, it is possible that some timbers are derived from the same tree. The value of the cross-match between samples POL-C13 and C31, from the body of the Gatehouse proper and a timber of the mezzanine floor respectively, is t=13, whilst that between samples POL-C18 and C19, the tiebeams of trusses B and C, respectively is t=12.5. At the time of sampling it was noted that a number of half- and possibly quarter-trees were to be found. A number of other cross-matches are found with values in excess of t=10.0 both within and between the main group and mezzanine floor timbers. It is likely that several other trees represented by these samples were growing close to each other in the same copse.

The roof timbers of the annex and its south arm were all probably felled in AD 1582. These timbers form a clearly coherent group but it is unlikely that any of the timbers used in the roof of the annex, or its south arm, are derived from the same tree, the t-values of the cross-matches between the samples from these beams being generally lower, and most of the beams seen to be whole timbers. It is likely however, that the trees used were growing within the same copse or stand of woodland.

Six other measured samples remain ungrouped and undated. All these undated samples have sufficient rings for reliable analysis and none show bands of compressed or distorted rings which might make cross-matching and dating difficult. This is not an unusual situation in tree-ring dating where a proportion of measured samples often do not date. Indeed, in this instance, the proportion is quite small, with only 16% of the samples remaining undated.

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Table 1: Details of samples from Polesworth Abbey Gatehouse, Polesworth, Warwickshire

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Annex roof					
POL-C01	North lower purlin, truss F–G	98	21C	AD 1485	AD 1561	AD 1582
POL-C02	South lower purlin, truss F–G	93	17C	AD 1490	AD 1565	AD 1582
POL-C03	North stud post, truss G	97	no h/s	------	-----	------
POL-C04	North lower purlin, truss E–F	72	21C	AD 1511	AD 1561	AD 1582
POL-C05	North principal rafter, truss E	86	18	AD 1483	AD 1550	AD 1568
POL-C06	South principal rafter, truss E	88	h/s	AD 1466	AD 1553	AD 1553
POL-C07	Collar, truss E	127	no h/s	AD 1361	------	AD 1487
POL-C08	North lower purlin, truss D–E	135	17C	AD 1448	AD 1565	AD 1582
POL-C09	South lower purlin, truss D–E	110	14	AD 1452	AD 1547	AD 1561
POL-C10	South principal rafter, truss D	75	no h/s	------	------	------
	Gatehouse 'proper'					
POL-C11	Brace to tiebeam from main north post, truss B	128	no h/s	AD 1114	------	AD 1241
POL-C12	Main north post, truss B	80	no h/s	AD 1194	------	AD 1273
POL-C13	Brace to tiebeam from south arcade post, truss B	124	h/s	AD 1184	AD 1307	AD 1307
POL-C14	East brace to plate from south arcade post, truss B	nm	---	------	------	------
POL-C15	Lower west brace from south arcade post, truss B	82	h/s	AD 1229	AD 1310	AD 1310
POL-C16	South arcade post, truss B	nm	---	------	------	------
POL-C17	South arcade plate, truss A–B	125	9	AD 1201	AD 1316	AD 1325
POL-C18	Tiebeam, truss B	125	h/s	AD 1184	AD 1308	AD 1308
POL-C19	Tiebeam, truss C	181	25	AD 1151	AD 1306	AD 1331
POL-C20	Brace to tiebeam from main north post, truss C	220	no h/s	AD 1095	------	AD 1314

Table 1: continued

Sample number	Sample location	Total Rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Gatehouse 'proper' continued					
POL-C21	South arcade post, truss C	113	13	AD 1214	AD 1313	AD 1326
POL-C22	South brace, crown post to collar, truss A	nm	17	------	------	------
POL-C23	Joist 6 (from east)	115	h/s	AD 1202	AD 1316	AD 1316
POL-C24	Joist 5	54	5	------	------	------
POL-C25	Joist 3	nm	---	------	------	------
POL-C26	Joist 1	65	20C	AD 1278	AD 1322	AD 1342
	Gatehouse 'proper' – mezzanine floor					
POL-C31	Joist 1 (from north)	138	4	AD 1183	AD 1316	AD 1320
POL-C32	Joist 2	80	h/s	AD 1238	AD 1317	AD 1317
POL-C33	Joist 3	102	no h/s	AD 1144	------	AD 1245
POL-C34	Joist 4	132	no h/s	AD 1163	------	AD 1294
POL-C35	Joist 5	84	34C	AD 1253	AD 1302	AD 1336
POL-C36	Joist 6	165	h/s	AD 1153	AD 1317	AD 1317
POL-C37	Joist 9 reused	60	h/s	------	------	------
POL-C38	Joist 11	189	h/s	AD 1127	AD 1315	AD 1315
POL-C39	Joist 12	175	h/s	AD 1142	AD 1316	AD 1316
POL-C40	Joist 13	153	33C	AD 1187	AD 1306	AD 1339
POL-C41	Joist 14	66	h/s	AD 1236	AD 1301	AD 1301

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Annex –south arm					
POL-C51	Collar, truss 1 = GG/FF	116	28C	AD 1467	AD 1554	AD 1582
POL-C52	East principal rafter, truss 1 = GG / FF	69	no h/s	------	------	------
POL-C53	Coupled rafter pair 6 (from north)–west side	71	no h/s	AD 1448	------	AD 1518
POL-C54	Coupled rafter pair 7–west side	75	no h/s	AD 1446	------	AD 1520
POL-C55	Coupled rafter pair 7–east side	106	h/s	------	------	------
POL-C56	Coupled rafter pair 8–west side	95	h/s	AD 1466	AD 1560	AD 1560
POL-C57	Collar, truss 2 (south gable)	nm	---	------	------	------

*h/s = the last ring on the sample is at the heartwood/sapwood boundary
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber
nm = sample not measured

Table 2: Results of the cross-matching of site chronology POLCSQ01 and relevant reference chronologies when first ring date is AD 1095 and last ring date is AD 1342

Reference chronology	Span of chronology	*t*-value	
East Midlands	AD 882–1981	12.2	(Laxton and Litton 1988)
'Severns', Castle Road, Nottingham	AD 1030–1334	11.6	(Howard *et al* 1996b)
Manor House, Abbey Green, Burton-on-Trent, Staffs	AD 1162–1339	10.3	(Howard *et al* 1998 unpubl)
Angel Choir, Lincoln Cathedral, Lincoln	AD 904–1257	10.2	(Laxton and Litton 1988)
England	AD 401–1981	9.1	(Baillie and Pilcher 1982 unpubl)
7–9 Stourport Road, Bewdley, Worcs	AD 1060–1301	8.8	(Arnold *et al* 2005)
51/2 High St, Burton-on-Trent, Staffs	AD 1156–1387	8.4	(Howard *et al* 1997)
England, London	AD 413–1728	8.1	(Tyers and Groves 1999 unpubl)

Table 3: Results of the cross-matching of site chronology POLCSQ02 and relevant reference chronologies when first ring date is AD 1446 and last ring date is AD 1582

Reference chronology	Span of chronology	*t*-value	
Sinai Park, Burton on Trent, Staffs	AD 1227–1750	9.4	(Tyers 1997)
East Midlands	AD 882–1981	9.3	(Laxton and Litton 1988)
Wales and West Midlands	AD 1341–1636	9.3	(Siebenlist-Kerner 1978)
England, London	AD 413–1728	9.3	(Tyers and Groves 1999 unpubl)
26 Westgate Street, Gloucester	AD 1399–1622	9.2	(Howard *et al* 1998)
MC10---H	AD 1386–1585	8.9	(Fletcher 1978)
England	AD 401–1981	8.5	(Baillie and Pilcher 1982 unpubl)
Stoneleigh Abbey, Stoneleigh, Warwicks	AD 1398–1658	7.9	(Howard *et al* 2000)

Table 4: Results of the cross-matching of sample POL-C07 and relevant reference chronologies when first ring date is AD 1361 and last ring date is AD 1487

Reference chronology	Span of chronology	*t*-value	
Sinai Park, Burton-on-Trent, Staffs	AD 1227–1750	7.5	(Tyers 1997)
East Midlands	AD 882–1981	7.2	(Laxton and Litton 1988)
Boughton Hall, Northamptonshire	AD 1355–1509	7.0	(Meirion-Jones *et al* 1987)
Governor's House, Newark, Notts	AD 1319–1453	6.4	(Howard *et al* 1986)
South-west transept, Lincoln Cathedral	AD 1372–1477	6.1	(Laxton and Litton 1988)
Ughill Manor, Bradfield, S Yorks	AD 1349–1504	6.0	(Howard *et al* 1994)
April Cottage, Rothley, Leics	AD 1343–1443	5.7	(Alcock *et al* 1990)
Barbican/Gatehouse, Warwick Castle	AD 1310–1503	5.2	(Howard 1995 unpubl)

Figure 1: Location of Polesworth Abbey, Warwickshire

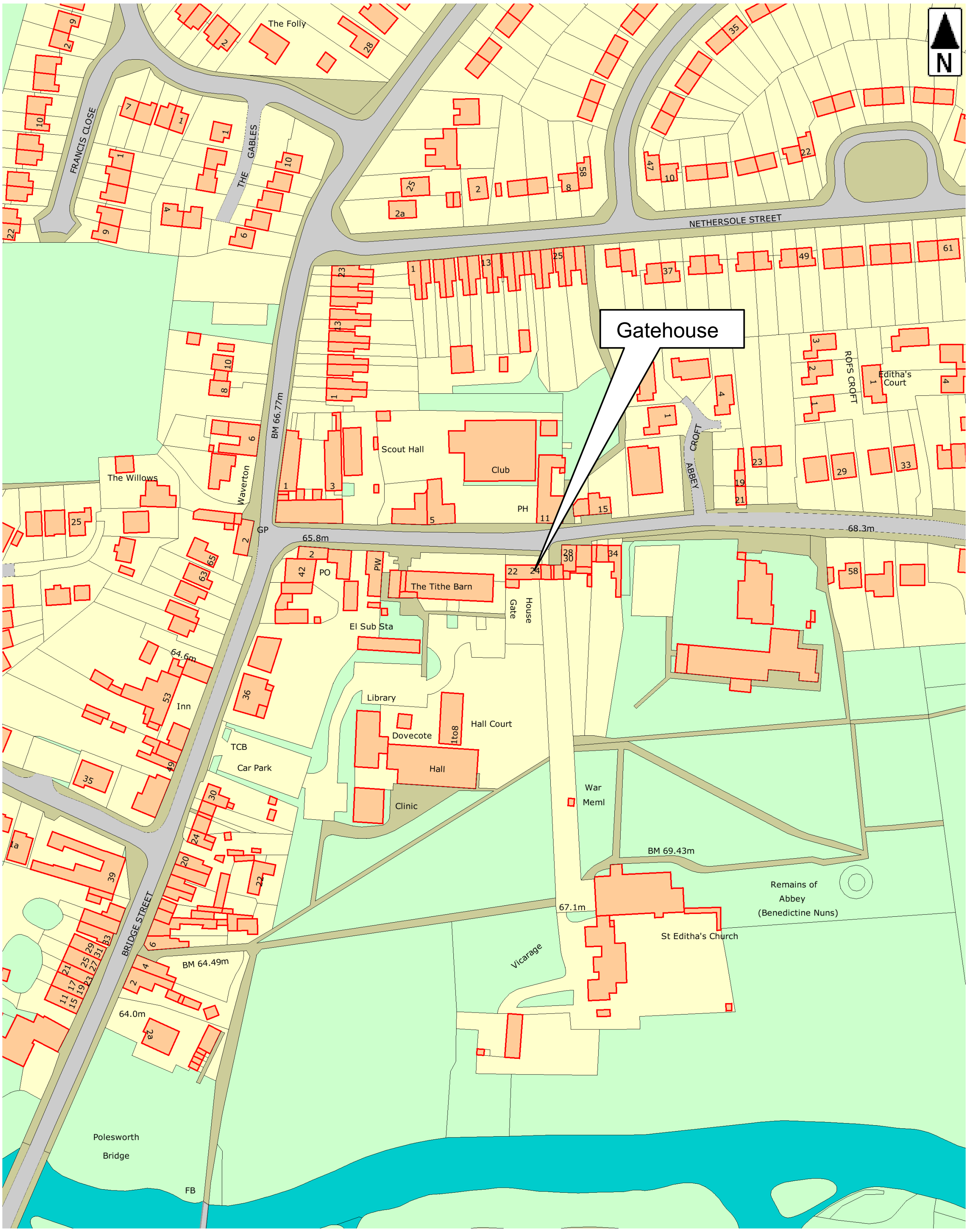


Figure 2: Location of Polesworth Abbey Gatehouse

Figure 3: Rear, or south view of Polesworth Abbey Gatehouse, showing the Gatehouse proper (to the right) with its carriageway, pedestrian portal, and door of stairway to mezzanine and upper floor, and the annex to the left with its short gabled arm, possibly a porch or staircase

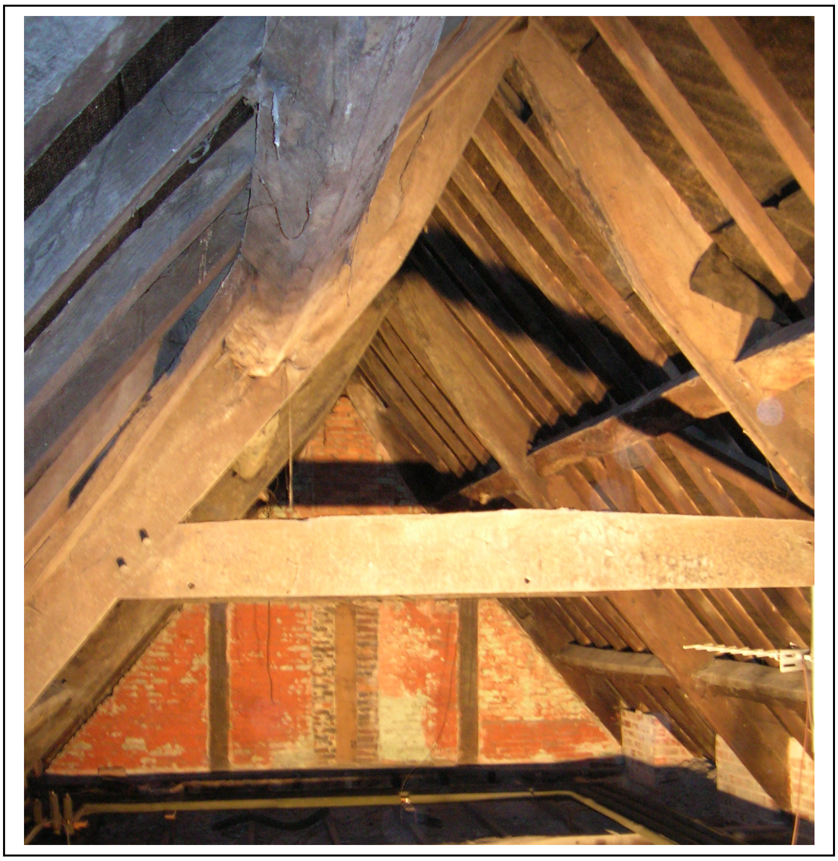


Figure 4a (top): View of trusses A (to right) and B (to left) of the Gatehouse proper
Figure 4b (bottom): View of the annex roof showing trusses E, F, and, at the far west gable, G

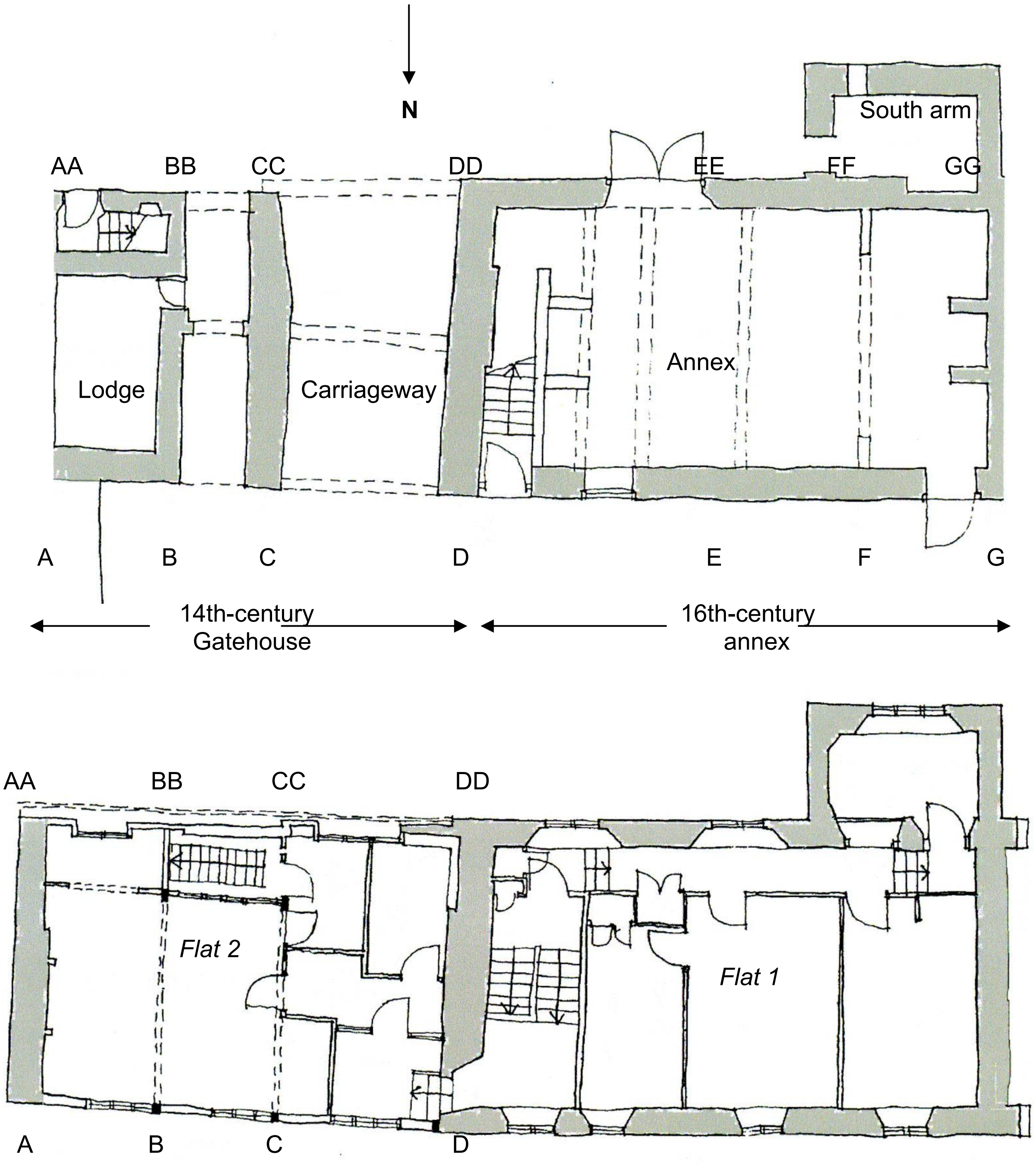


Figure 5: Schematic plans of ground floor (top) and first floor (below)
(after Jean and Bob Meeson)

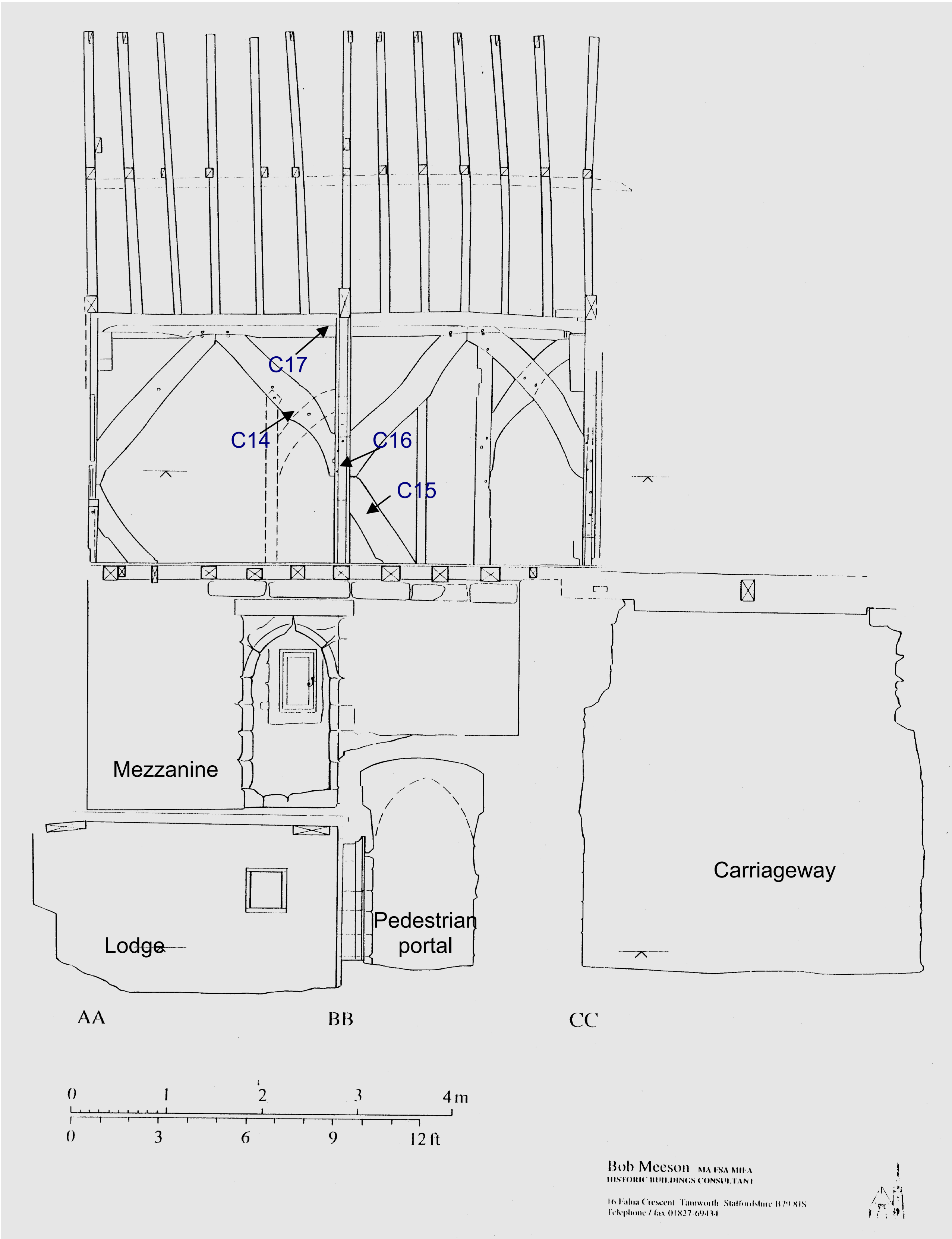


Figure 6a: Gatehouse; drawing to show sample locations from mezzanine ceiling and south arcade (viewed looking south) (after Jean and Bob Meeson)

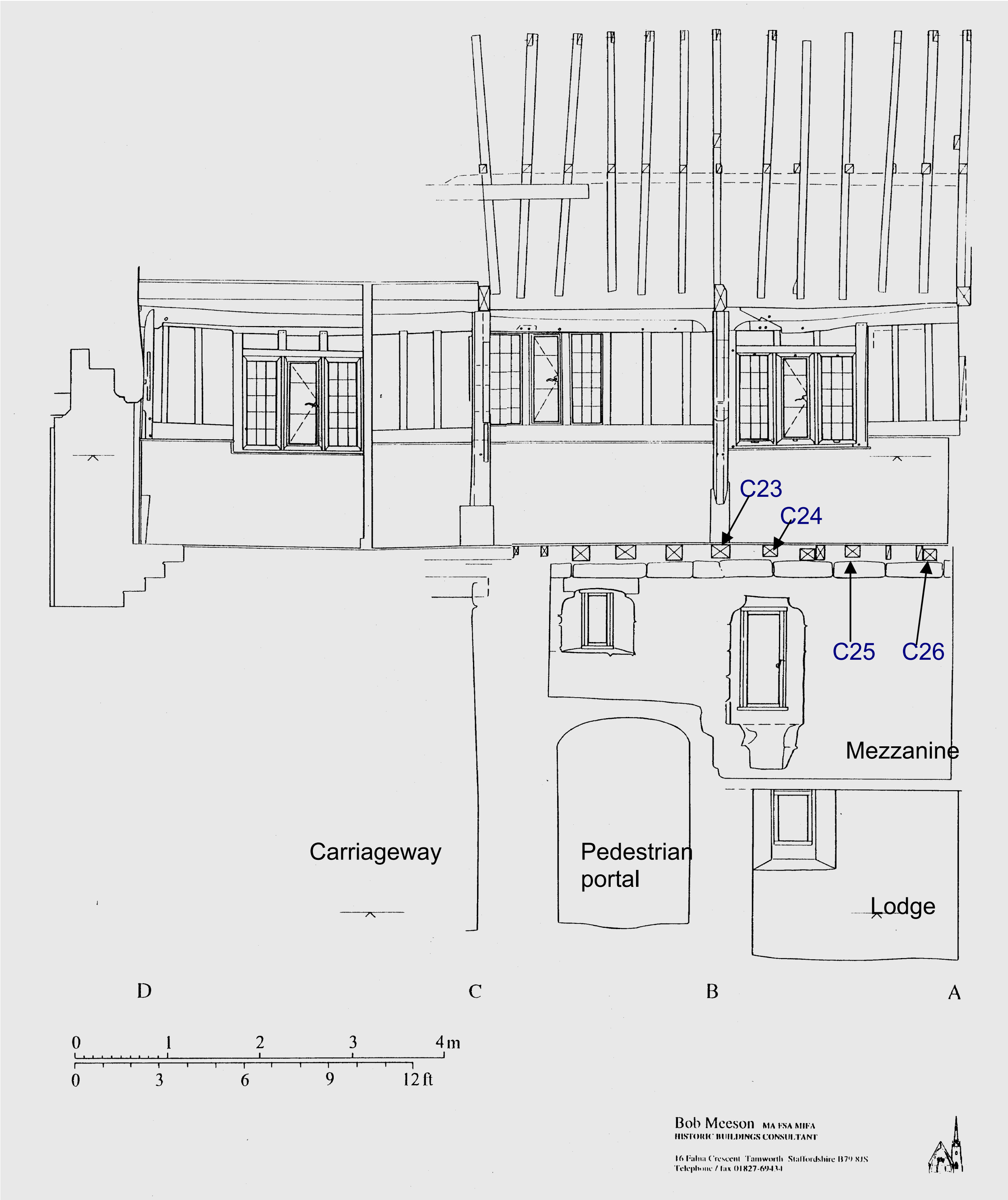


Figure 6b: Gatehouse; drawing to show sample locations from the mezzanine ceiling (viewed looking north) (after Jean and Bob Meeson)

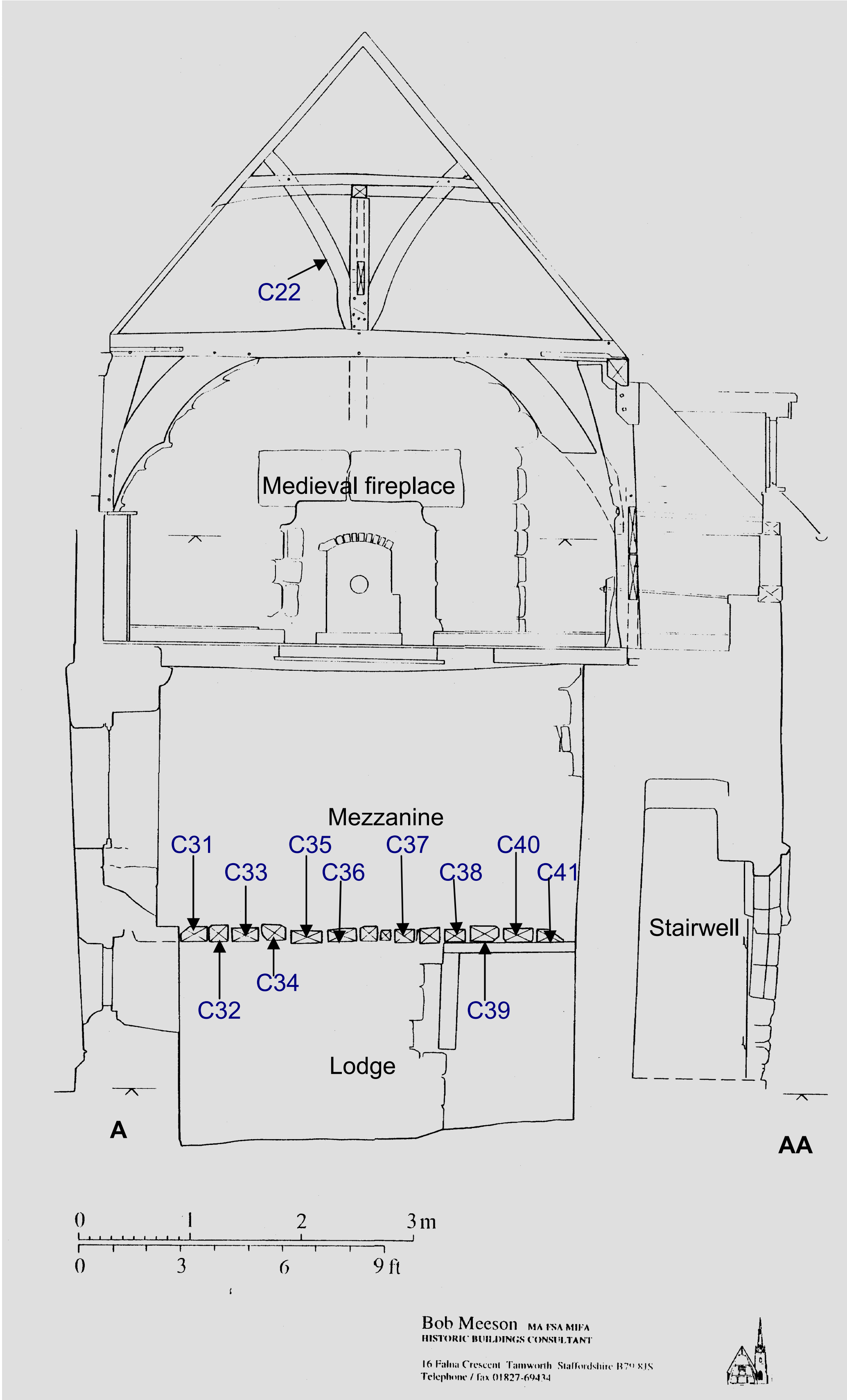


Figure 6c: Gatehouse; drawing to show sample locations from the mezzanine floor joists and roof (viewed looking east) (after Jean and Bob Meeson)

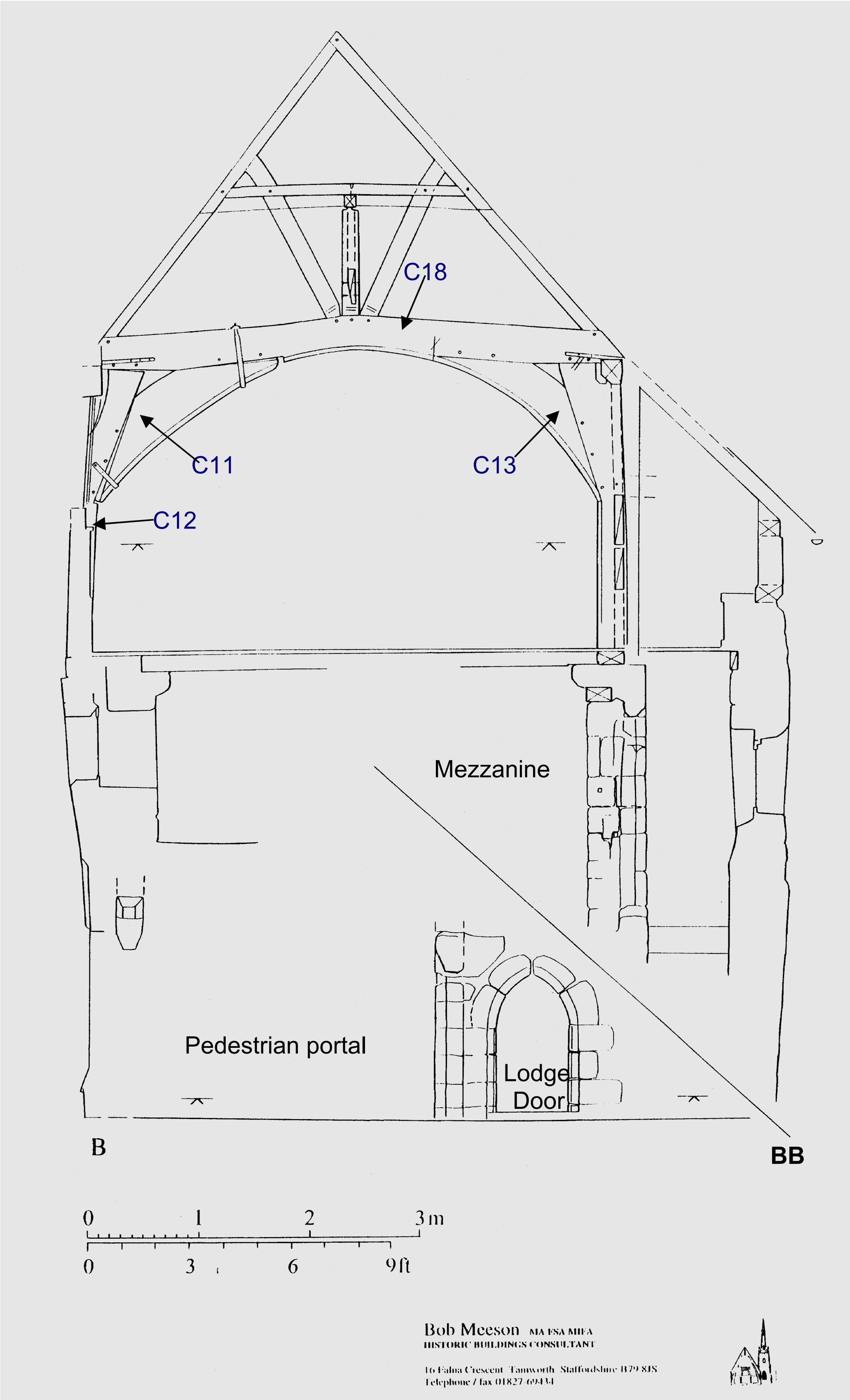


Figure 6d: Gatehouse; drawing to show sample locations from truss B (viewed looking east) (after Jean and Bob Meeson)

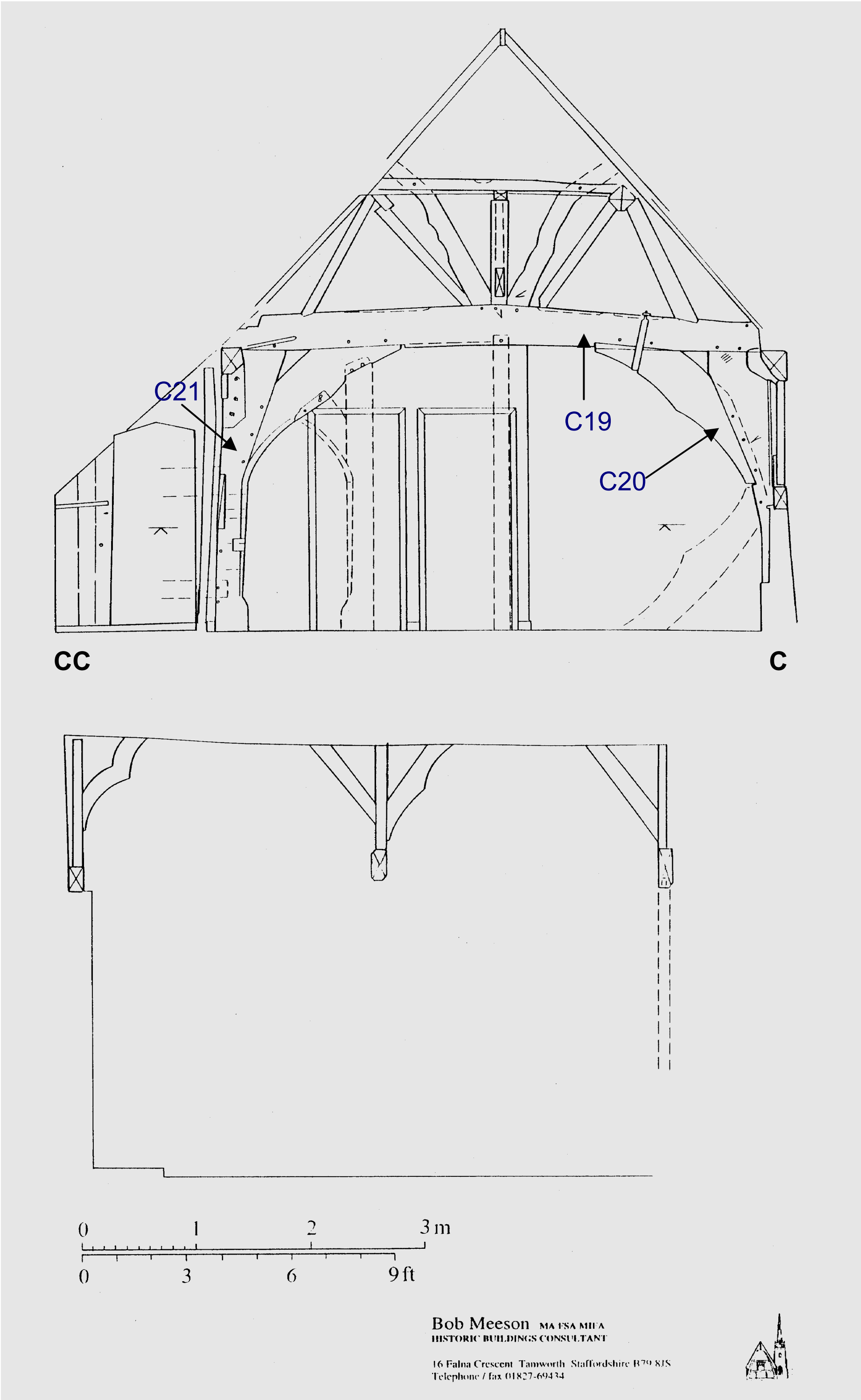


Figure 6e: Gatehouse; drawing to show sample locations from truss C (viewed looking west) (after Jean and Bob Meeson)

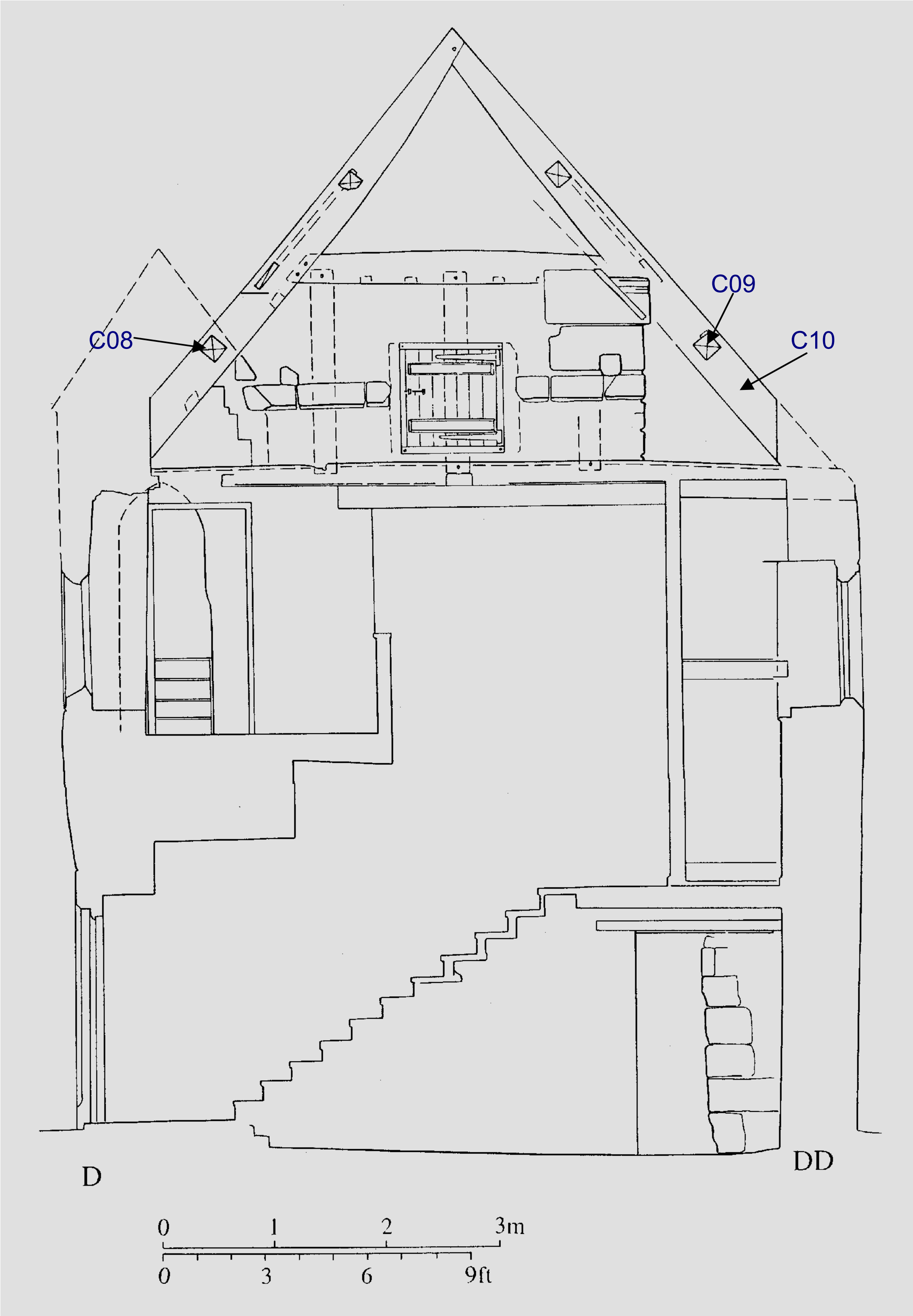


Figure 6f: Annex; drawing to show sample locations from truss D (viewed looking east) (after Jean and Bob Meeson)

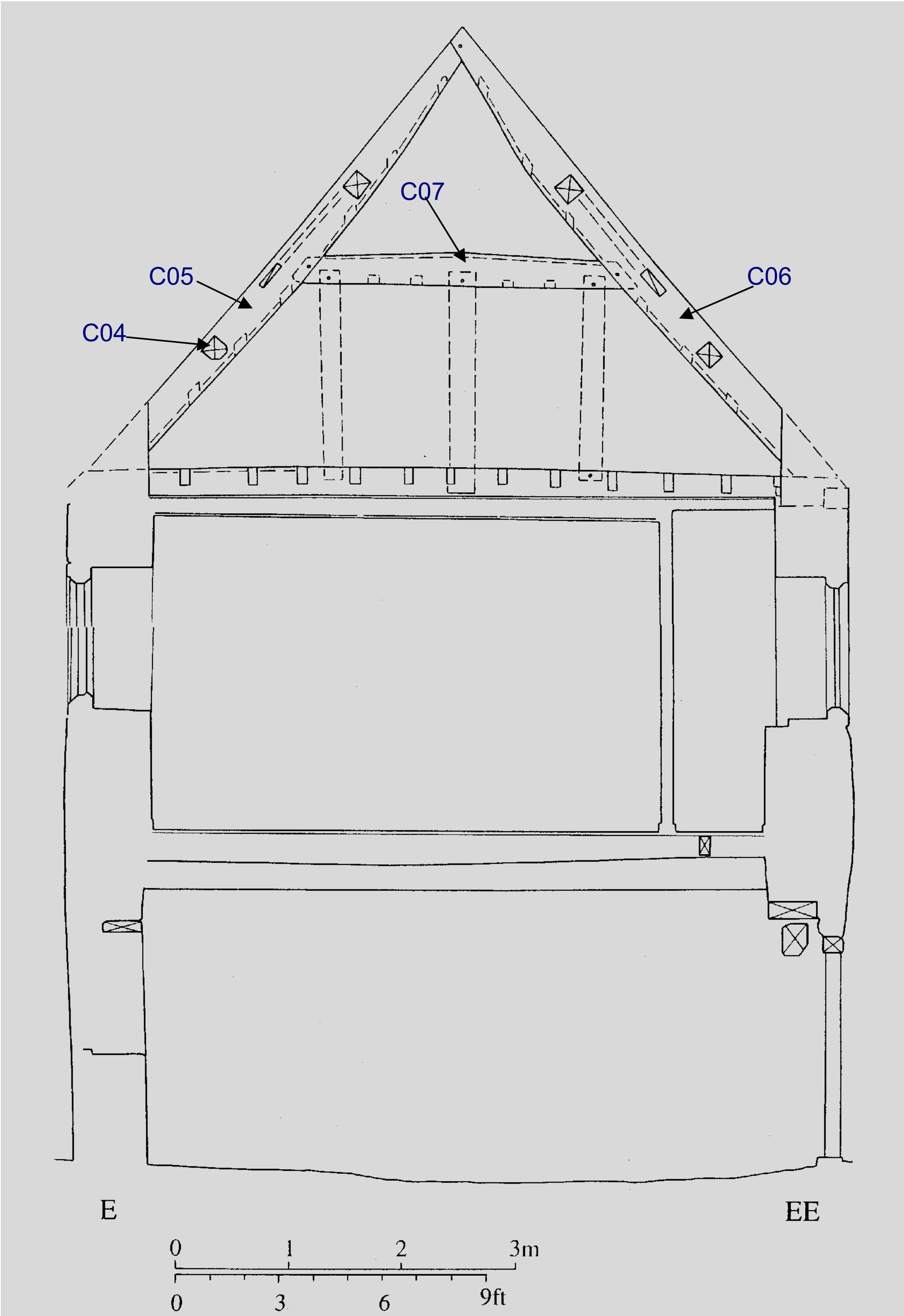


Figure 6g: Annex; drawing to show sample locations from truss E (viewed looking east) (after Jean and Bob Meeson)

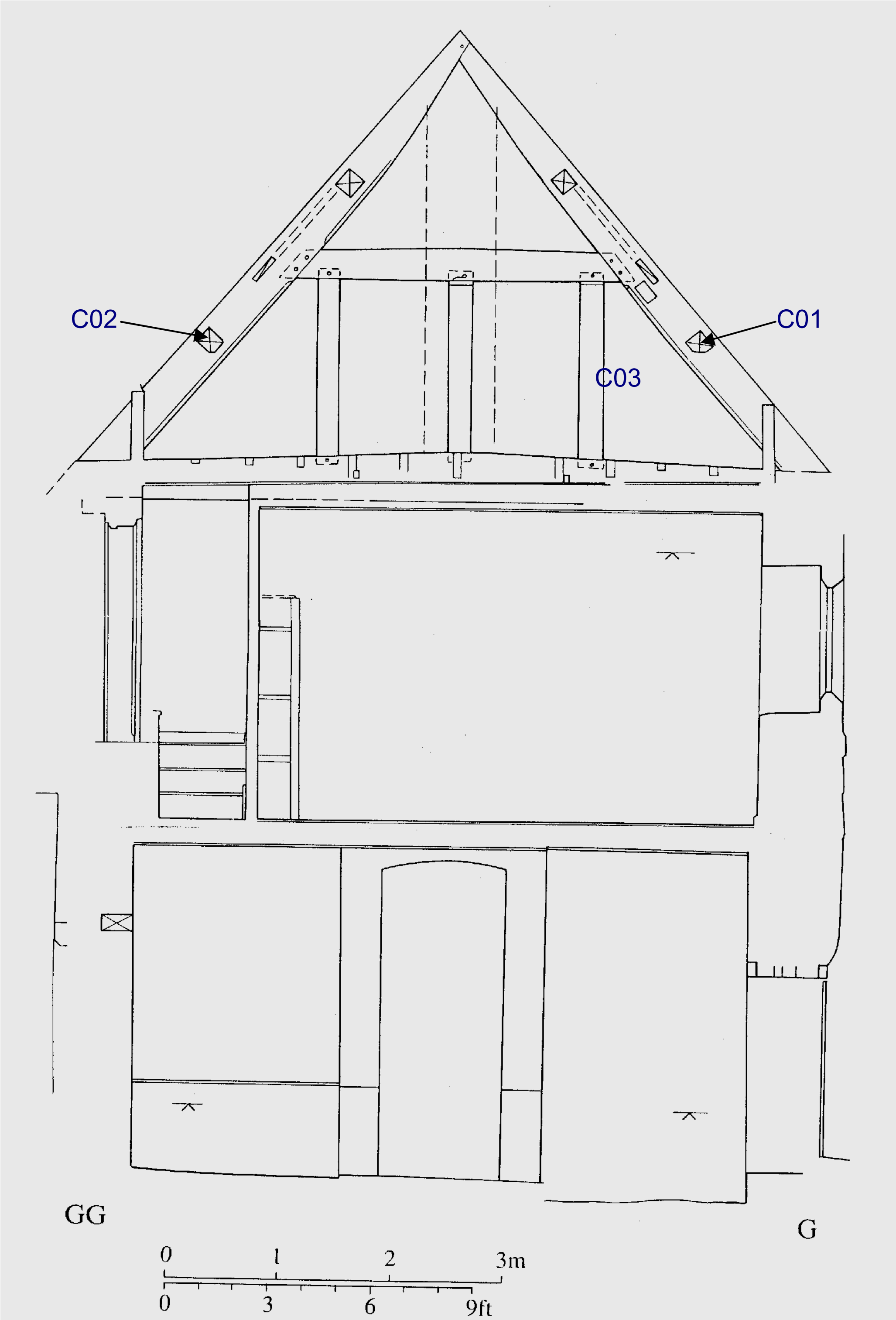


Figure 6h: Annex; drawing to show sample locations from truss G (viewed looking west) (after Jean and Bob Meeson)

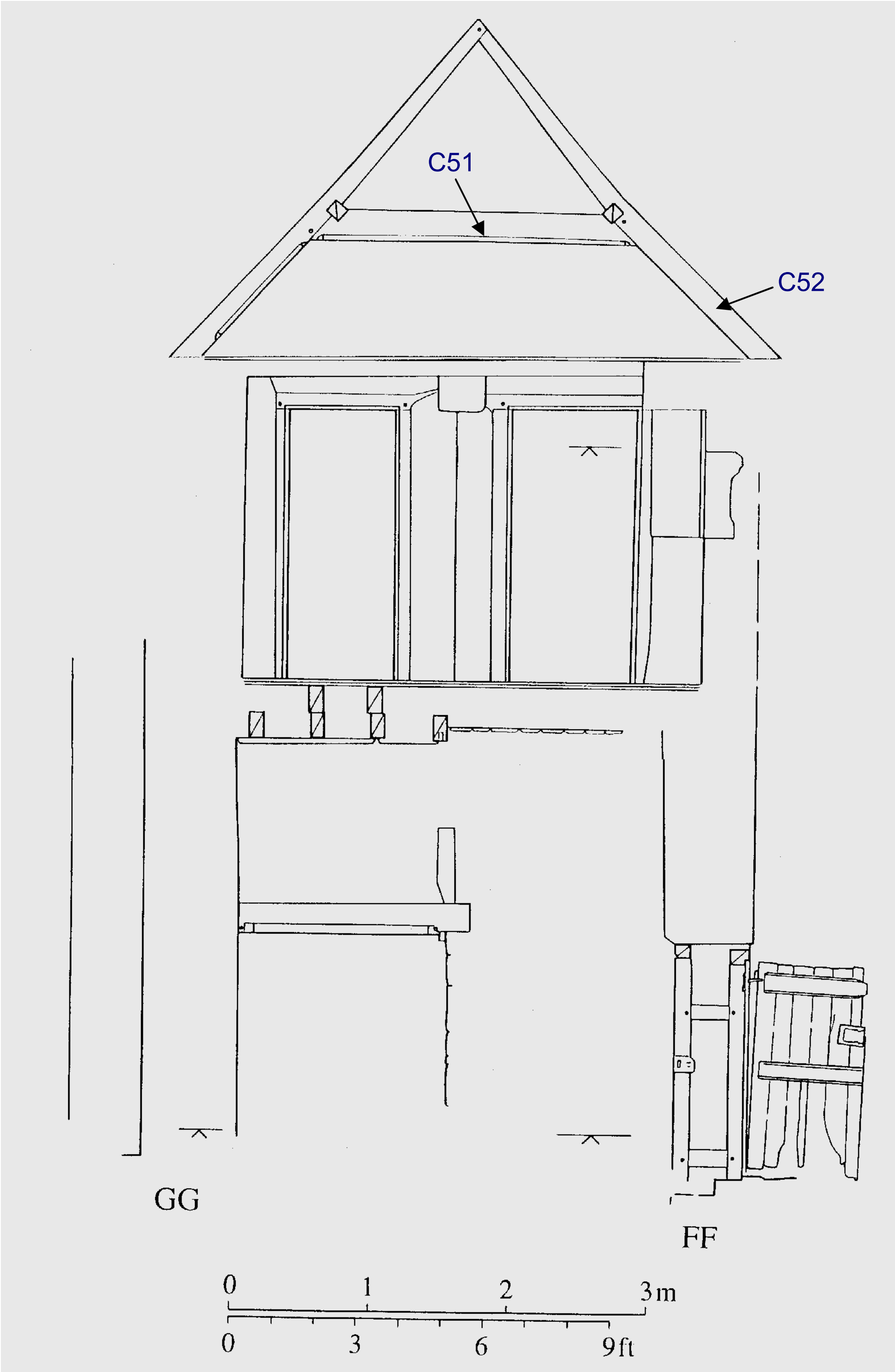
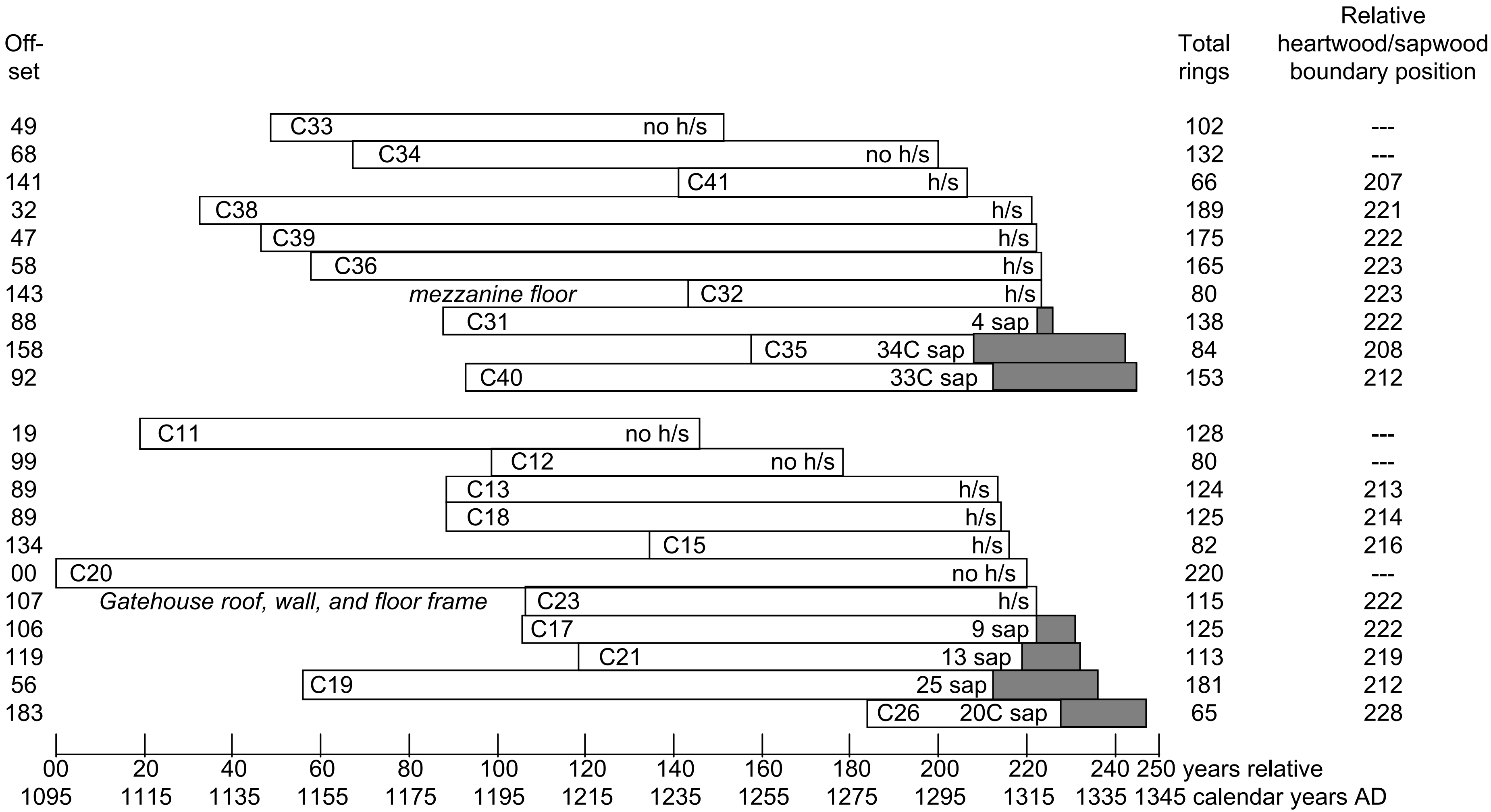


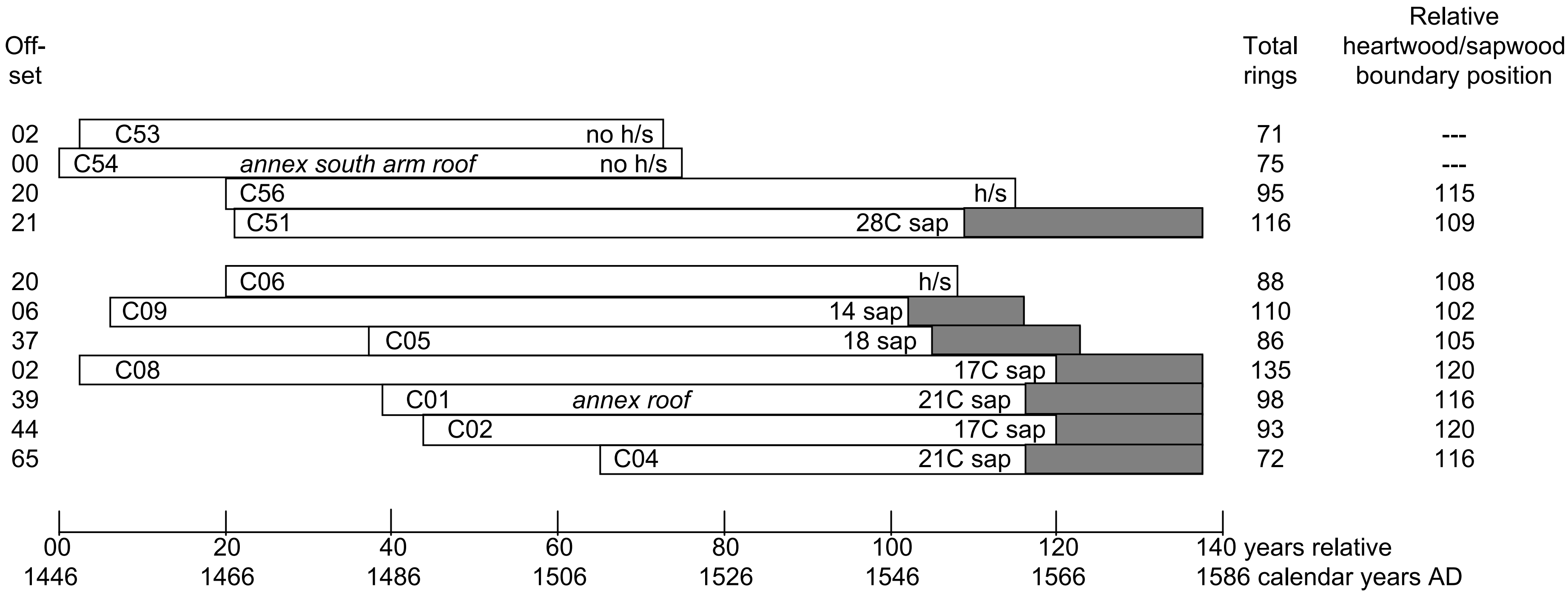
Figure 6i: Annex south arm; drawing to show sample locations from section GG/FF (viewed looking south) (after Jean and Bob Meeson)



White bars = heartwood rings, shaded area = sapwood rings

C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber

Figure 7: Bar diagram of the samples in site chronology POLCSQ01



white bars = heartwood rings, shaded area = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree

Figure 8: Bar diagram of the samples in site chronology POLCSQ02

Data of measured samples – measurements in 0.01 mm units

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POL-C01A 98
118  74  68  66  83  98  92 134 119 148  86  84  47  65  84  69  53  55  81  76
 66  94 106 111 136  91  94 131 105 115 149 142 116 150 245 156 153 284 284 208
161 284 239 306 246 191 327 183 196 190 287 208 204 235 200 180 170  80 163 156
156 141  68 178 252 220 287 221 233 176 248 179 138 216 203 244 197 238 174 238
166 173 149 169 214 224 205 179 206 219 198 209 194 149 156 200 167 183
POL-C01B 98
121 112 100 109 141 154  87 148  70  96  78  97  53  53  93  61  59  66  73  93
 60  68  84  95 102 108 109 134 105 121 137 147 123 150 241 144 155 267 276 196
171 295 228 300 240 171 302 188 203 198 264 204 194 220 178 166 151  91 133 145
157 139  69 167 267 217 294 209 225 190 251 173 145 217 206 244 224 236 164 237
163 168 144 185 214 235 192 176 203 221 206 204 202 145 154 202 170 189
POL-C02A 93
 48  68  92 104 185 194 265 293 127 105 207 321  87  50  52  73 122 115 111 138
 91 172 233 179 163 241 285 211 274 326 202 189 245 160 175 143 231 233 207 124
117 185  86 105 109 197 167 144 151 165 200 160  91 131 139 172 126  94 128 134
152 204 130 158 151 142 108 114 119 147 148 227 233 258 317 242 109 107 160 288
281 349 324 230 206 149 114 173 160 167 206 185 199
POL-C02B 93
 52  67 101  92 189 193 270 274 119 111 228 320  89  38  60  68 129 126 115 139
 80 146 186 209 176 227 256 228 278 335 191 195 244 163 175 140 233 232 209 132
116 192  80 119 108 208 170 155 160 162 190 152  89 135 151 186 143  84 130 137
151 199 125 149 167 133 112 111 109 158 154 229 235 264 310 240 117  84 129 225
300 332 257 215 181 181 110 166 164 148 233 176 207
POL-C03A 97
231 218 216 244 259 216 296 284 281 235 348 328 237 175 196  71  68  99 152 140
109 125 158 239 345 222 289 442  98  68  65  74  99  92  96 123 163 142 131 194
166 158 183 180 368 251 228 333 254 225 170 198 198 251 233 253 333 223 284 180
309 205 182 248 237 213 179 274 190 148 177 135 182 139 140 176 180 145 148 151
149 138 138 149 149 135 137 160 130 135 103 174 210 210 203 174 162
POL-C03B 97
221 233 210 232 248 200 281 334 272 254 327 332 250 184 191  70  83  98 148 149
127 105 175 236 344 222 296 451  98  70  76  68 111  91  98 127 156 139 137 187
165 167 180 182 352 270 237 347 258 216 171 192 209 234 242 266 335 218 282 172
318 209 172 261 233 212 190 278 186 146 183 136 173 146 140 180 182 147 143 151
161 128 139 147 160 139 138 158 137 124 111 166 223 207 190 186 168
POL-C04A 72
138 182 218 163 151 218 129 177 234 217 189 170 260 186 169 212 198 244 202 150
317 123 169 163 224 239 175 186 166 203 156 103 155 152 166 114  83 106 112 183
177 189 158 128 146  90  81 109 111 145 168 174 209 188 108  78  71 140 137 168
234 181 172 151 231 118 133 131 128 168 217 220
POL-C04B 72
136 199 237 169 159 227 119 186 257 219 186 174 275 180 145 197 204 249 198 159
304 143 166 170 213 234 178 195 159 221 159  95 149 153 169  98  82 109 115 165
174 175 171 156 134  89  86  95 135 133 171 185 201 168 104  87  77 137 146 155
223 197 170 146 242 116 137 139 146 157 208 215
POL-C05A 86
151 195 146 129 170 157 153 176 107 115 145 167 158 166 126  88 118 113 125 109
122 128  99 123  85 118  99 128 105 157 135 129 128 147 124 158 159 118 127 133
120 121  99 148 130 123 122  97 101  95  95 105  96 101 101 106 101  96 112  69
108  73  80  90  71  92 103 100 122 131 134  81 121  75  99 102 105  87  84  85
 73  72  74  63  82  79
POL-C05B 86
132 195 151 133 168 155 145 181 106 122 138 174 141 169 112  96 116 112 131 103
124 130  98 128  92 107 110 113 110 161 136 114 142 144 129 163 139 119 134 130
123 116 106 136 115 129 117  89 120  81 103  92 104 101 110 102  97 103  97  76
101  74  75 100  71  89  93 114 115 117 134  82 117  73  92 111 100  77  88  82
 77  71  63  79  72  69
POL-C06A 88
225 210 176 224 289 231 172 191 181 260 233 200 160 244 261 245 154 207 260 194
201 241 200 187 183 115 156 209 192 169 197 137 126 152 126 102 100  98 129 108
 96  94 113 123 150 158 203 184 160 183 219 179 233 230 155 201 191 162 177 109
173 199 173 152  85 156 110 130 110 160 165 142 154 145 141 169 106 123 120  98
132  72 131 142 148 185 164 200
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213 244 212 194 189 118 144 213 197 163 196 138 128 139 128  96 108 112 119  98
 96  88 118 123 137 158 212 178 156 175 208 177 233 227 145 206 183 178 183 112
165 204 173 148  92 142 118 123 129 160 167 147 153 146 156 154 102 131 107  98
131  75 124 134 159 181 165 202
POL-C07A 127
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292 313 260 193 240 226 272 249 108 122 117 153 164 183 166 189 200 263 384 437
328 335 354 168 150 128 144 169 197 164 145 235 235 198 180 155 178 198 156 277
164 220 308 280 138 103 120 149 161 140 180 165 166 157 128 214 201 177 170 187
175 154 215 159 137 167 126 162 170 160 196 200 196 228 179 209 223 169 145 182
167 161 178 161 140 115 161 179 221 240 185 115 112 129 181 177 166 165 275 261
221 236 201 218 222 176 263
POL-C07B 127
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281 339 262 185 252 216 286 248 107 119 113 153 162 185 173 184 195 276 371 437
337 331 355 170 157 138 143 164 202 172 136 235 223 195 190 154 191 178 151 287
168 207 321 285 145 104 110 150 156 129 190 167 160 151 150 206 209 167 179 182
180 157 216 155 137 161 145 160 160 160 191 211 210 222 174 214 209 174 152 166
151 163 179 174 118 130 158 178 223 245 176 107 116 123 183 170 164 167 281 273
229 222 206 236 209 175 265
POL-C08A 135
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195 349 279 172 132 111 186 283 235 159 119 135 156 100 112 146 187 131 125 134
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 67 106 103 155  98  88  99 129  96  99  69  89 122 174 184
POL-C08B 135
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193 347 265 181 118 122 172 252 240 161 134 134 139  94 116 147 179 146 102 149
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 84 144  98  97 118 100  78  97 104  84 152 192 101 111 108 126 109  91 174 165
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POL-C09A 110
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POL-C10B 75
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POL-C11A 128
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151 144 174 137 108 130 105 138 186 208 135 181 190 209 183 145 137 133 124 173
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 80 124 107 122  84 122 104 116
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149 146 160 136 110 134  90 140 186 240 130 171 179 223 175 145 137 125 119 189
153 143 164 148 140 127 119 128 126 104 125 139 175 125 151 122 157 147 101 143
133 171 183 159 117 107 122 148 123 142 159 118 147 124 130 138 140  73  74  75
 83 131  99 107  97 138  98 110
POL-C12A 80
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211 283 297 308 190 175 304 269 205 204 292 269 323 206 376 334 225 188 146 114
185 269 170 290 217 244 224 205 147 326 248 303 317 299 247 270 179 187 168 208
195 292 238 237 117 150 178 209 227 238 188 166 161 145 157 182 175 237 226 267
POL-C12B 80
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204 289 218 225 137 156 179 206 216 220 198 164 161 142 156 176 191 236 225 261
POL-C13A 124
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120 155  75 111
POL-C13B 124
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113 138 172 146 201 191 187 111  71  77  75 127  77 119 101  93  88  90  98 169
150 100 127 205 121 102 100 118  97 136 107 165 149 125 128 117 118 116 158 164
128 120  60  59  63  79  93 115 116 146 185 123 103  80 110 150 174 188 156 152
134 134 146 109  88 149 150 146 280 197 147 119  95 127 107  99 115 173 167 194
127 104  82 107
POL-C15A 82
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 77 105
POL-C15B 82
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114  93 105 114 134  93 111  91 123 115 107 140 138  72  86  68  62  96  70  79
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POL-C17A 125
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255 210 220 249 256 248 246 223 158 183 178 127 124 153 159 125 217 170 187 216
122 138 184 172 160 175 211 148 213 140 129 125 135 149 228 154 155 153 144 150
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POL-C18A 125
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111 123 110  83 114 131 152 166 130 129 153 169 171 179 130 134 161 185 147 145
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 78 109 108  95  84
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POL-C20A 220
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202 171 135  84 127 146 167 169 183 208 207 168 173 206 225 193 187 222 176 180
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POL-C20B 220
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APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building'* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

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

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure 2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

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

Figure 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.

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

Figure 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.

Figure 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.

2. ***Measuring Ring Widths***. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. ***Cross-matching and Dating the Samples***. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984-1995).

   This is illustrated in Figure 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a *site sequence* of the building being dated and is illustrated in Figure 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig 5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called *sapwood* rings, are usually lighter than the inner rings, the *heartwood*, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure 2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

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

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

5. ***Estimating the Date of Construction***. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55). Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

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

7. ***Ring-width Indices***. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar 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	

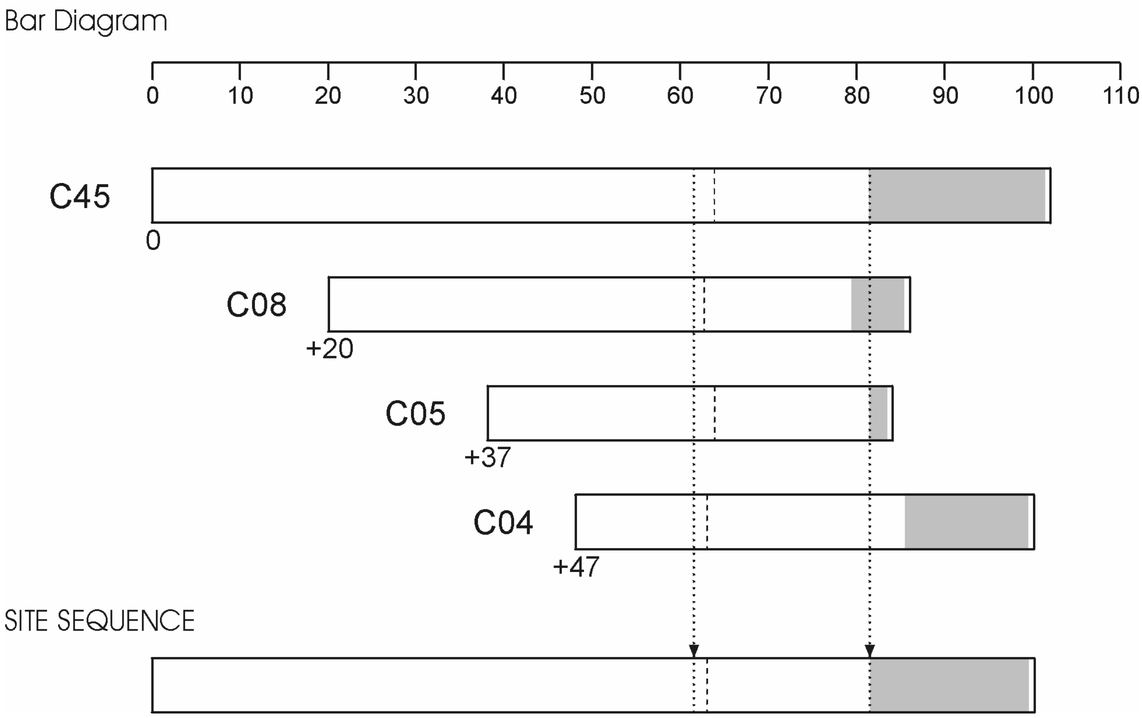


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

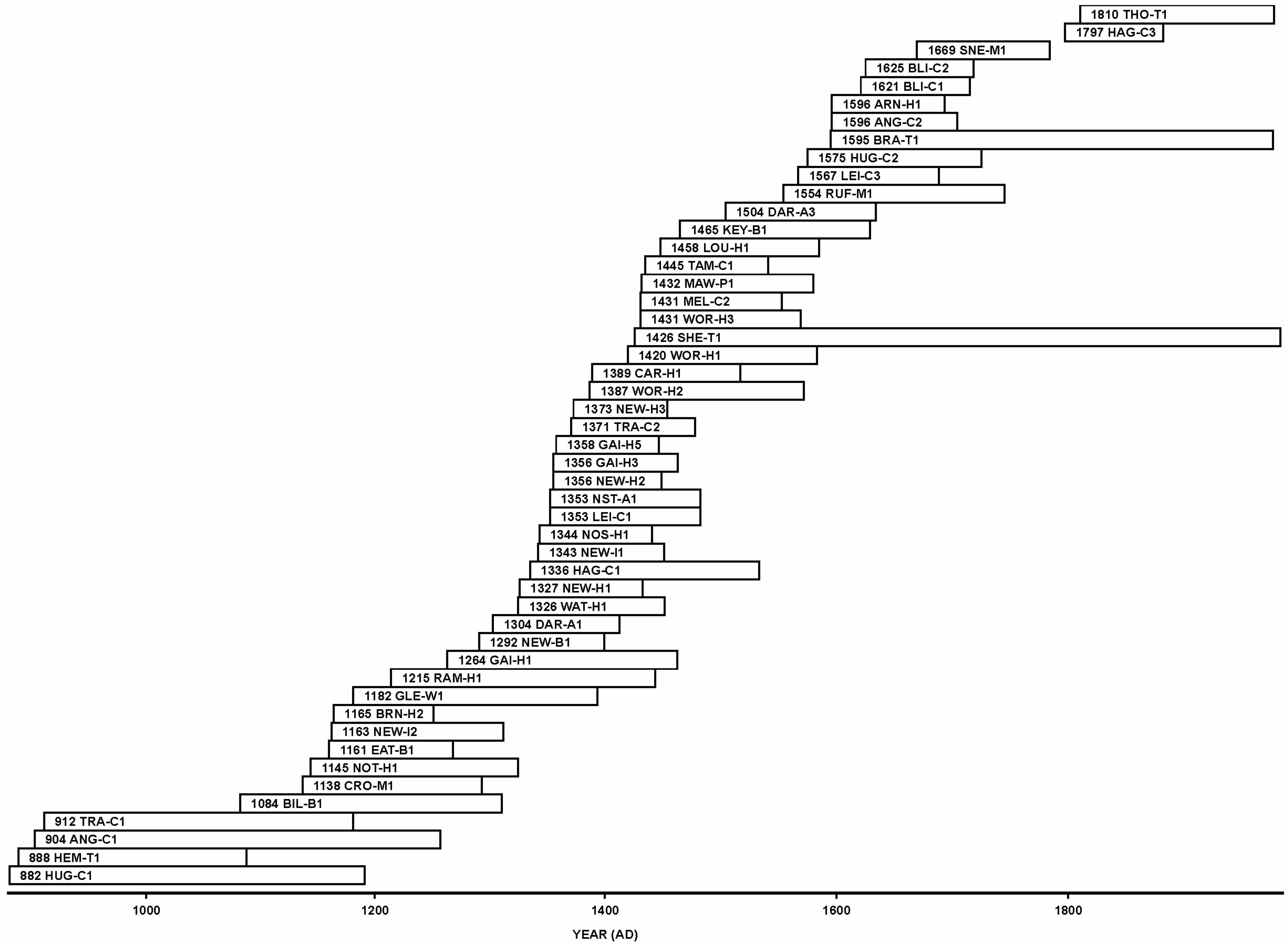
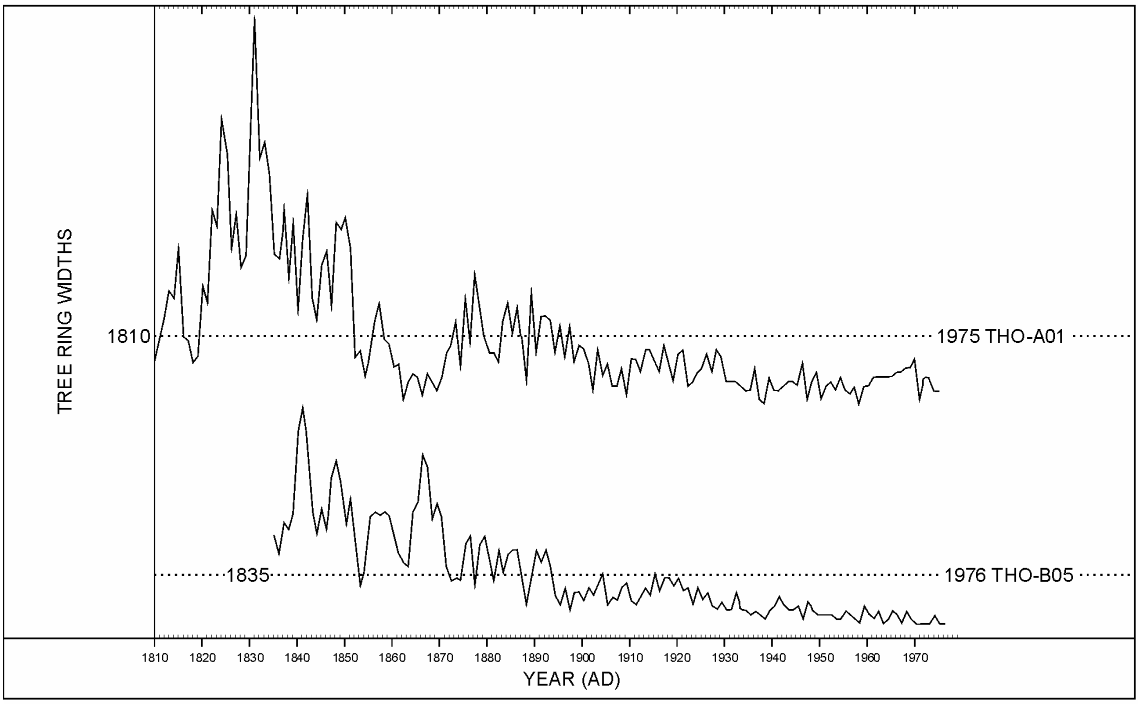


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

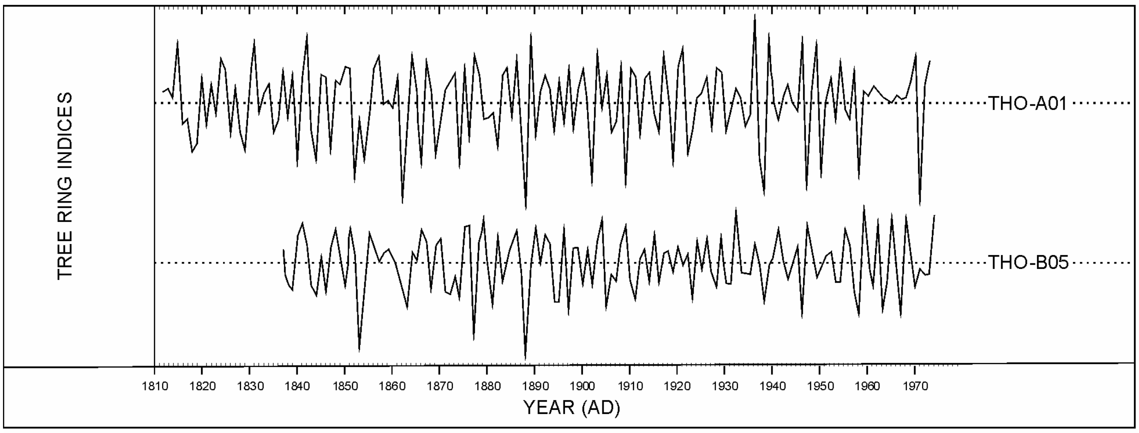


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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

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