TREE-RING ANALYSIS OF TIMBERS FROM THE GUILDHALL COMPLEX AND THE PEDAGOGUE'S HOUSE, STRATFORD-UPON-AVON, WARWICKSHIRE

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Summary

Core samples were obtained from 23 timbers of the medieval Guildhall complex at Stratford-upon-Avon (the main Guildhall range and its south range). Another 10 cores were obtained from the adjacent Pedagogue's House. Analysis of 25 of these samples (8 being unsuitable for analysis) produced two dated site chronologies and dated another sample individually.

The first site chronology, SUABSQ01, comprises 12 samples, all from the Guildhall complex, of overall length 99 rings. These are dated as spanning AD 1305–1403. The second site chronology, SUABSQ02, comprises seven samples, all from the Pedagogue's House. Of overall length 126 rings, this spans AD 1377–1502. A further single sample, SUA-B19, was dated individually, its 80 rings spanning AD 1353–1432.

Interpretation of the sapwood indicates that the majority of dated timbers of the Guildhall complex were cut in a single programme of felling, this estimated to have occurred AD 1410–35. Documentary evidence suggests the building was erected from AD 1417–18 and was completed by AD 1425. One timber, from an inserted ceiling, is later, this probably not being felled before AD 1447.

Conventionally the Pedagogue's House is thought to date to AD 1427–28, when it is documented that a school house was under construction. Tree-ring analysis shows, however, that the dated timbers are likely to have been felled much later, in AD 1502.

Introduction

The Grade 1-listed main and south ranges of the Guildhall (NGR SP20055472), and the Pedagogue's House adjacent to the east (NGR SP20075471), are at the core of the King Edward VI Grammar School in Church Street, Stratford-upon-Avon (Figs 1 and 2). Until the current programme of research by Field Archaeology Services, York, Ltd, the complex (Fig 3) was believed to have been built in three stages, the south range, built as a house, being the primary phase, the northern end of the main Guildhall range being constructed next, with the southern end of the main Guildhall range being a slightly later addition (Parker 1987). All three sections were thought to date to the early-fifteenth century, there being a documentary reference of AD 1417–18 to a building under construction (BRT 1/3/31). The Pedagogue's House had been identified with a school house documented as under construction in the late AD 1427–28 (BRT 1/3/38). Views of the Guildhall and the Pedagogue's House are given in Figures 4a/b.

Description

The Guildhall main range (see Fig 3)

The ceiling of the ground floor room is supported by curved brackets rising from the main structural posts in the east and west walls. Where these brackets join the main posts, a series of carpenter's marks is visible. The curved brackets rising from the posts support transverse beams running across the room with a simple chamfer moulding discernible. These in turn support a beam running down the centre of the room, which is more heavily moulded, with a series of curves and hollows visible. Running out from the central beam are the timber joists, which support the floor above and project beyond the wall plate to form the jetties visible from the outside.

The roof structure is supported by principal posts running up from the ground floor. In the two pairs of principal posts at the south end of the hall grooves can be identified, which, although now in-filled with timber, suggest that partitions originally divided these two bays into two smaller rooms. This is further supported by the form of the trusses above. The four open trusses in the room take two different forms. The two trusses to the north (trusses 2 and 3) have queen post roofs, with additional central posts, and further braces above the collar. The two trusses to the south (trusses 4 and 5) have a different structure, with five vertical posts below the collar, and three above (an illustration of one of the southern trusses, truss 5, is given in Figure 5a). The form is similar to that used in the gable ends of the hall (trusses 1 and 6). Significantly, the posts and rafters of both of these trusses have grooves associated with the insertion of panels, confirming the evidence on the posts below of room divisions at this end of the now open hall. This evidence clearly indicates that the upper hall was originally of three bays occupying the northern end of the building, with a further two rooms occupying the southern two bays of the structure.

Despite the two forms of trusses, the remainder of the roof structure is uniform, with the trusses supporting two rows of tenoned/clasped purlins which in turn support the common rafters. Additional support is provided by curved wind braces, which rise from the principal rafters to the purlins at both levels. In places the wind braces have not survived, but the pegging and mortices in the principal rafter confirm that originally all the purlins were braced. The inference, therefore, is that the entire main range is all one phase of construction and hence one date.

The south range (see Fig 3)

The ceiling structure of the ground floor room is relatively simple, with two bridging beams running between the principal posts which support joists of similar proportions to those used in the construction of the Guildhall. Both beams have been reinforced, with another timber fixed underneath the original. To the west the original beam cannot be seen, although it is assumed it is in the plastered section above the later insertion. The lower beam is attached to the principal posts with metal brackets. In the centre the beam is attached to the post at the north with a wooden bracket and to the south with an additional timber fastened to the full length of the principal post. Although much of this original beam, and all of the one to the west, is obscured, it appears that they use a much plainer form than the beams in the ground floor of the main range of the Guildhall. A long-sectional view of the south range is given in Figure 5b.

The roof of the south range is indicative of several phases of use of the first floor room. The original roof structure is best indicated by the truss above the central principal posts (truss 8). It can probably be assumed that this roof form continued over the eastern end of the south range, a section which was demolished before AD 1852. The form of this surviving original truss also represents a similar roof form to the original open trusses in the main range of the Guildhall, albeit on a smaller scale. A tiebeam rests on the two principal posts, with queen posts then rising to the collar. A row of purlins, clasped by the collar and the principal rafter, supports the common rafters. Curved wind braces, again similar to those observed in the upper hall of the Guildhall, rise from the wall plate to the purlins at either side of the principal rafter and at both gable ends (trusses 7 and 9). This roof form is indicative of a fifteenth-century date, with the trusses clearly intended to be seen from below.

This roof, however, was ceiled over, and the highly moulded beams of this ceiling also survive. This must have taken place after the painting of the wall panels in the west gable end, which, stylistically, suggest that this part of the roof was visible at least in the AD 1480s. The ceiling is formed into squares, with an additional transverse beam crossing the room on either side of the surviving original tiebeam and a bridging beam running west to east across the centre of the room. Where these reach the walls they are bonded into additional wall plates which have been added to the originals. An extra beam has also been attached to the surviving original tiebeam, presumably allowing the complete concealment of all the original timbers, leaving only their later counterparts on display. Stylistically, this ceiling form, and the moulding on the beams, would suggest a sixteenth-century date for this work.

Pedagogue's House (see Fig 3)

The upper floor is divided into two large rooms. The distinctive feature of the northern room is the survival of two open trusses. Both trusses have a tiebeam resting on principal posts. The truss to the north, truss 1 (see Fig 6a), also has curved arch braces rising from the principal posts to the tiebeam. Empty mortices with associated peg holes in the southern truss (truss 2) suggest that this originally had the same braces, but they have subsequently been removed, probably in order to allow the better use of the first floor room. Above the tiebeam, queen posts rise to support a collar. Between the collar and the principal rafters are clasped purlins which support the remainder of the rafters. Curved arch braces also rise from the principal rafters to the purlins, to provide additional support. The trusses also show evidence of other redundant structural features, although it is not possible to ascertain what might be original. There is evidence of lap joints of various sizes towards the western side of the southern truss. The northern truss, truss 1, has a large mortice located centrally on the truss and smaller mortices in the western of the two queen posts.

The southern of the two rooms on the first floor has one original roof truss remaining (truss 3, see Fig 6b, truss 4 in the south gable wall having been largely replaced) incorporated in the northern elevation of the room. Truss three takes a different form to those observed in the room to the north, with a form of close studding used between the tiebeam and the collar and between the collar and the rafters. Clasped purlins run from the truss supporting the common rafters. Curved wind braces run from the principal rafters to the purlins providing additional bracing. As in the main range of the Guildhall, this different truss form seems to indicate the use of this truss as a partition in the original layout of the Pedagogue's House.

It seems likely that the current partitions reflect the original layout of the upper floor. This is largely determined by looking at the roof structure, the trusses of which appear to be largely original. In the northern room, where there are two open trusses (trusses 1 and 2) in a queen-post form, it is clear that the first floor has been inserted and that originally this room would have had an open hall structure. This may correspond to the construction of the Pedagogue's House as a school house, with this large room serving as the school. In the southern room, the different form of the surviving truss (truss 3), suggests that, in contrast to the northern section, this truss reflects an original partition, creating a room at ground and first-floor level.

Sampling

Sampling and analysis by tree-ring dating of the Guildhall and of the adjacent Pedagogue's House were commissioned by English Heritage. The purpose of this was to inform detailed survey and recording being undertaken in preparation of a conservation management plan. It was hoped that tree-ring dating would establish the date of the various elements of site with greater reliability and accuracy, and demonstrate any sequential development of the buildings.

From the material available a total of 33 samples was obtained by coring. Each sample was given the code SUA-B (for Stratford-upon-Avon, site 'B') and numbered 01–33. From the main range of the Guildhall a total of 12 samples, SUA-B01–12, was obtained, with samples being obtained from both the roof and ground-floor ceiling timbers. A further 11 samples, SUA-B13–23, were obtained from the roof of the south range of the Guildhall. A total of 10 samples, SUA-B24–33, all but one from the roof, was obtained from the Pedagogue's House. The approximate positions of these samples are marked on plans produced and supplied by Field Archaeology Specialists Ltd, York, shown here as Figures 7a–c. Details of the samples are given in Table 1. In this Table the trusses, frames, and other timbers have been located following the scheme of the drawings provided, being further located on a north-south, or east-west, basis as appropriate.

The Laboratory would like to take this opportunity to thank the staff of King Edward VI Grammar School for their help and cooperation during sampling and for their enthusiasm for the programme of tree-ring analysis. We would also like to thank Field Archaeology Specialists Ltd, York, for providing drawings and for the description of the buildings provided in the introduction above.

Analysis

Each of the 33 samples obtained was prepared by sanding and polishing. It was seen at this point that eight samples had too few rings for reliable dating (ie less than 54) and these samples were rejected from this programme of analysis. The ring-widths of the remaining 25 samples were, however, measured, the data of these measurements being given at the end of this report. The data of these measurements 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 8 and 9.

The first site chronology, SUABSQ01, comprises 12 samples with an overall length of 99 rings. This site chronology was compared to a number of relevant reference chronologies for oak, this indicating a cross-match when the date of the first ring is AD 1305 and the date of the last ring is AD 1403. Evidence for this dating is given in the *t*-values of Table 2.
The second site chronology, SUABSQ02, comprises 7 samples with an overall length of 126 rings. Site chronology SUABSQ02 was also compared to a number of relevant reference chronologies for oak. This indicated a cross-match when the date of the first ring is AD 1377 and the date of the last ring is AD 1502. Evidence for this dating is given in the *t*-values of Table 3.

Both site chronologies were compared with the six remaining measured but ungrouped samples but there was no further satisfactory cross-matching. Each of the six samples was then compared individually with a full range of reference chronologies for oak. This indicated a cross-match for one further sample, SUA-B19, when the date of its first ring is AD 1353 and the date of its last ring is AD 1432. Evidence for this dating is given in the *t*-values of Table 4.

Interpretation and conclusion

Analysis by dendrochronology of 25 measured samples from this site has produced two dated site chronologies and dated one sample individually.

None of the samples obtained from either the main or south range of the Guildhall retains complete sapwood and thus the precise felling date of any of the timbers cannot be accurately determined. Several dated samples do, however, retain the heartwood/sapwood boundary, the average date of the boundary being AD 1395. The usual 95% confidence limit for the amount of sapwood on mature trees from this part of England is 15–40 rings, which would give the timbers represented an estimated felling date in the range AD 1410–35. Such an estimated felling date would fit very firmly with documentary evidence that a building was under construction in AD 1417–18.

There appears to be no significant difference in the dates of the heartwood/sapwood boundaries on samples from either the roof of the main range of the Guildhall or those from the ground floor ceiling, neither is there any significant difference between the samples from either end of this range, as once had been thought. The inference, therefore, is that the main range of the Guildhall is built of timber cut in a single phase of felling, and that it is of a single phase of construction.

There is also little difference in the dates of the sapwood boundaries on the samples from the main range of the Guildhall and those from most of the timbers of the south range. Thus, while the Field Archaeology Services survey shows that it is possible, on the basis of structural evidence, to show that the south range postdates the main range, this cannot be confirmed by dendrochronology, and in any case it is not likely to be by more than a year or two. The dated timbers from both the main and south range of the Guildhall show high levels of similarity suggesting that they are potentially derived from a single woodland source. This could be taken as supporting the probability that the timbers were felled at roughly the same time.

The exception is sample SUA-B19, which is certainly later than the other dated samples from the south range. This sample has a last measured, heartwood, ring date of AD 1432. Being without the heartwood/sapwood boundary, it is not possible to indicate a felling date range for the timber, except to say that it is unlikely to be before AD 1447. This timber is from the ceiling thought, from archaeological and documentary evidence, to have been inserted in the sixteenth century. The tree-ring date confirms that it is likely to be inserted but, given that other samples from the ceiling, SUA-B18, B20, and B21, are unmeasured, this is based on the dating of only one ceiling timber.

The Pedagogue's House

Seven samples from the Pedagogue's House have been dated. One sample, SUA-B33, retains complete sapwood, with a last ring date of AD 1502. This is thus the felling date of the timber represented. The relative position of the heartwood/sapwood boundary on the other six dated samples from this building is generally consistent with a single felling date and it is likely that they represent timbers which were all felled in AD 1502 as well.

The only exception to this single felling might be represented by sample SUA-B24, which has a relatively late heartwood/sapwood transition date of AD 1491. Were this timber to have been felled in AD 1502 it would of necessity have had only 11 sapwood rings. While this figure is below the usual minimum of 15 sapwood rings, it is not at all unknown, and indeed it might be expected that amongst a group of 33 samples, one or two samples would have sapwood ring numbers outside the 95% confidence limit.

This programme of tree-ring dating has, therefore, provided a new insight and some clarity to this otherwise slightly problematical building. Whereas prior to the most recent survey it had been thought that the main range of the Guildhall had been built in two stages, with a further range then being added to the south some time later, it can be shown that all these elements are largely of one single date, and almost certainly are those buildings referred to in the documentary evidence of AD 1417.

Furthermore, it can now be shown that the Pedagogue's House, which was thought to date to AD 1427–28, was built of timber felled in AD 1502.

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Table 1: Details of samples from the Guildhall and Pedagogue's House, Stratford-upon-Avon

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Guildhall - main range roof timbers					
SUA-B01	Tiebeam, truss 2	62	h/s	------	------	------
SUA-B02	Lower middle stud post, truss 2	nm	---	------	------	------
SUA-B03	Lower middle stud post, truss 3	54	h/s	AD 1342	AD 1395	AD 1395
SUA-B04	Tiebeam, truss 4	89	19C	------	------	------
SUA-B05	Collar, truss 4	76	no h/s	AD 1314	------	AD 1389
SUA-B06	Lower middle stud post, truss 4	86	9	AD 1316	AD 1392	AD 1401
SUA-B07	Tiebeam, truss 5	87	h/s	AD 1312	AD 1398	AD 1398
SUA-B08	Lower middle stud post, truss 5	72	h/s	AD 1323	AD 1394	AD 1394
	Ground floor ceiling timbers					
SUA-B09	West joist 3	nm	--	------	------	------
SUA-B10	West joist 4	79	h/s	AD 1320	AD 1398	AD 1398
SUA-B11	West joist 18	69	no h/s	AD 1320	------	AD 1388
SUA-B12	West joist 25	82	h/s	AD 1311	AD 1392	AD 1392
	Guildhall - south range first-floor ceiling and roof					
SUA-B13	Collar, centre truss (truss 8)	85	5	AD 1319	AD 1398	AD 1403
SUA-B14	Tiebeam, centre truss (truss 8)	54	4	------	------	------
SUA-B15	North queen post, centre truss (8)	71	h/s	AD 1326	AD 1396	AD 1396
SUA-B16	South queen post, centre truss (8)	96	h/s	AD 1305	AD 1400	AD 1400
SUA-B17	North purlin, truss 7–8	54	19	AD 1350	AD 1384	AD 1403

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood Rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Guildhall, south range first-floor ceiling and roof					
SUA-B18	Longitudinal ceiling beam, truss 7–8	56	h/s	------	------	------
SUA-B19	North ceiling beam, bay 6	80	no h/s	AD 1353	------	AD 1432
SUA-B20	South ceiling beam, bay 6	nm	---	------	------	------
SUA-B21	South ceiling beam, bay 7	nm	---	------	------	------
SUA-B22	North common rafter 6	nm	---	------	------	------
SUA-B23	South common rafter 13	nm	---	------	------	------
	Pedagogue's House					
SUA-B24	Tiebeam, truss 2	115	h/s	AD 1377	AD 1491	AD 1491
SUA-B25	Collar, truss 2	54	h/s	------	------	------
SUA-B26	East queen strut, truss 2	nm	---	------	------	------
SUA-B27	East purlin, truss 1–3	72	h/s	AD 1404	AD 1475	AD 1475
SUA-B28	West purlin, truss 1–3	85	h/s	AD 1403	AD 1487	AD 1487
SUA-B29	West wall post, bay 2	69	h/s	AD 1405	AD 1473	AD 1473
SUA-B30	Collar, truss 3	66	no h/s	AD 1380	------	AD 1445
SUA-B31	East purlin, truss 3 – south gable	70	h/s	AD 1401	AD 1470	AD 1470
SUA-B32	East rafter, south gable	nm	---	------	------	------
SUA-B33	East common rafter 15	89	28C	AD 1414	AD 1474	AD 1502

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

Table 2: Results of the cross-matching of site chronology SUABSQ01 and relevant reference chronologies when first ring date is AD 1305 and last ring date is AD 1403

Reference chronology	Span of chronology	*t*-value	
Upwich, Droitwich, Worcestershire	AD 946–1415	10.1	(Groves and Hillam 1997)
The Post Office, Oxhill, Warwicks	AD 1322–1447	8.9	(Alcock *et al* 1989)
Worcester Cathedral	AD 1286–1424	8.4	(Arnold *et al* 2003)
Ashleworth tithe barn, Gloucestershire	AD 1319–1475	8.1	(Bridge 2002)
2 School Road, Wellesbourne, Warwicks	AD 1287–1429	7.2	(Alcock *et al* 1989)
East Midlands	AD 882–1981	7.1	(Laxton and Litton 1988)
Mercer's Hall, Gloucester	AD 1289–1541	6.9	(Howard *et al* 1996)
Ann Hathaway's Cottage, Stratford-upon-Avon, Warwicks	AD 1319–1462	6.7	(Alcock *et al* 1991)

Table 3: Results of the cross-matching of site chronology SUABSQ02 and relevant reference chronologies when first ring date is AD 1377 and last ring date is AD 1502

Reference chronology	Span of chronology	*t*-value	
Sinai Park, Staffordshire	AD 1227–1750	7.6	(Tyers 1997)
Lower Brockhampton gatehouse, Herefordshire	AD 1368–1543	7.3	(Nayling 2001)
Tusmoore Park, Oxon	AD 1359–1545	7.2	(Howard *et al* 1992)
Thatched Cottage, Hill Wootton, Warwicks	AD 1392–1469	7.0	(Alcock *et al* 1989)
Naas House, Lydney, Glos	AD 1373–1568	6.9	(Howard *et al* 1998a)
Southern England	AD 1083–1981	6.8	(Bridge 1988)
26 Westgate Street, Gloucester	AD 1399–1622	6.7	(Howard *et al* 1998b)
Mercer's Hall, Gloucester	AD 1289–1541	6.5	(Howard *et al* 1996)

Table 4: Results of the cross-matching of sample SUA-B19 and relevant reference chronologies when first ring date is AD 1353 and last ring date is AD 1432

Reference chronology	Span of chronology	*t*-value	
Ashleworth tithe barn, Gloucestershire	AD 1319–1475	6.7	(Bridge 2002)
April Cottage, Rothley, Leics	AD 1343–1443	6.3	(Alcock *et a*l 1990)
Ann Hathaway's Cottage, Stratford-upon-Avon, Warwicks	AD 1319–1462	5.9	(Alcock *et al* 1991)
Redroofs, Sawbridge, Warwicks	AD 1355–1448	5.9	(Howard *et al* 1995)
The Post Office, Oxhill, Warwicks	AD 1322–1447	5.5	(Alcock *et al* 1989)
England, London	AD 413–1728	5.4	(Tyers and Groves 1999 unpubl)
Upwich, Droitwich, Worcestershire	AD 946–1415	5.4	(Groves and Hillam 1997)
Mercer's Hall, Gloucester	AD 1289–1541	5.3	(Howard *et al* 1996)

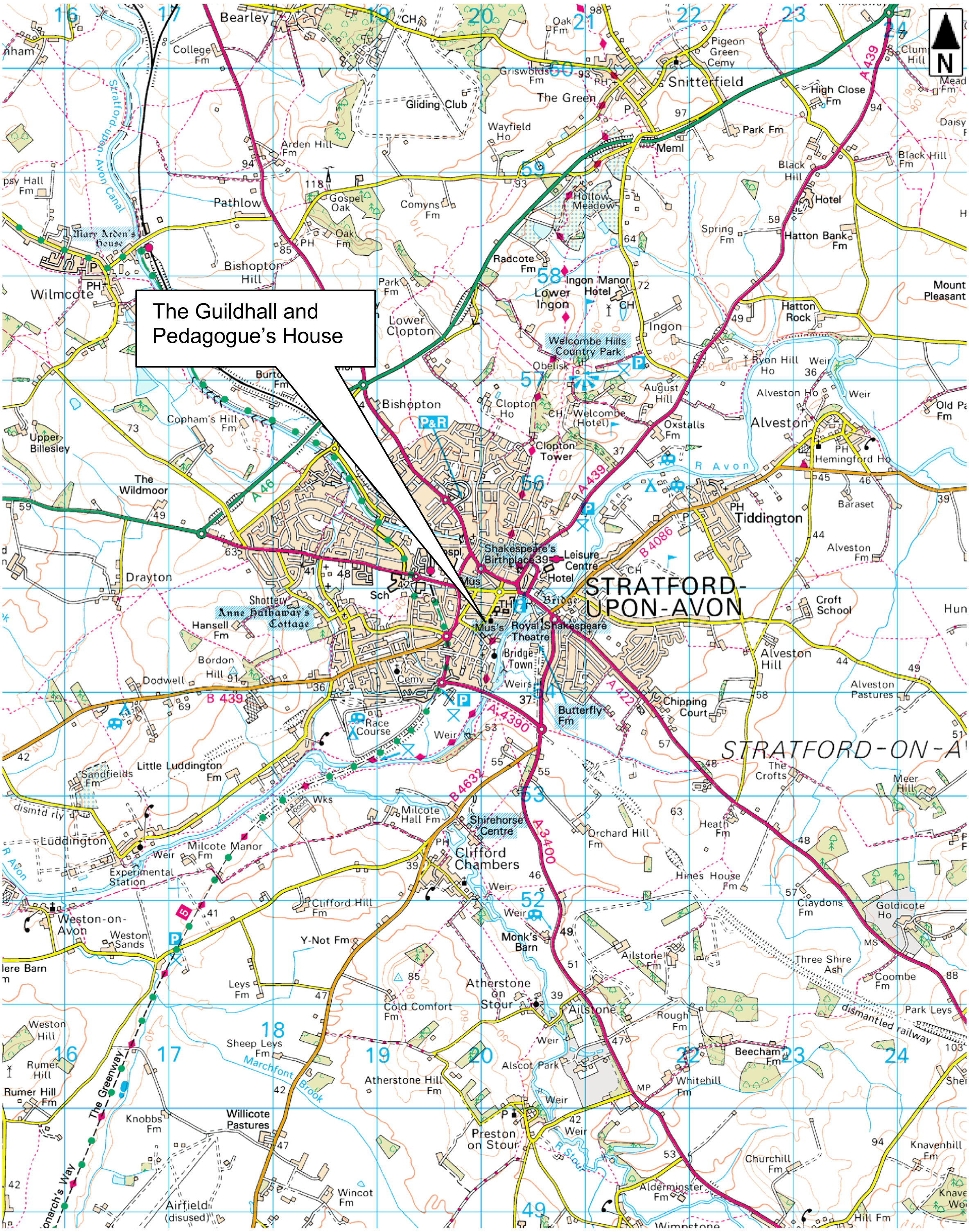

Figure 1: Map of Stratford-upon-Avon, showing the location of The Guildhall and Pedagogue's House. This map is based upon Ordnance Survey material with the permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office. © Crown Copyright. Unauthorised reproduction infringes Crown Copyright and may lead to prosecution or civil proceedings. English Heritage. 100019088. © English Heritage

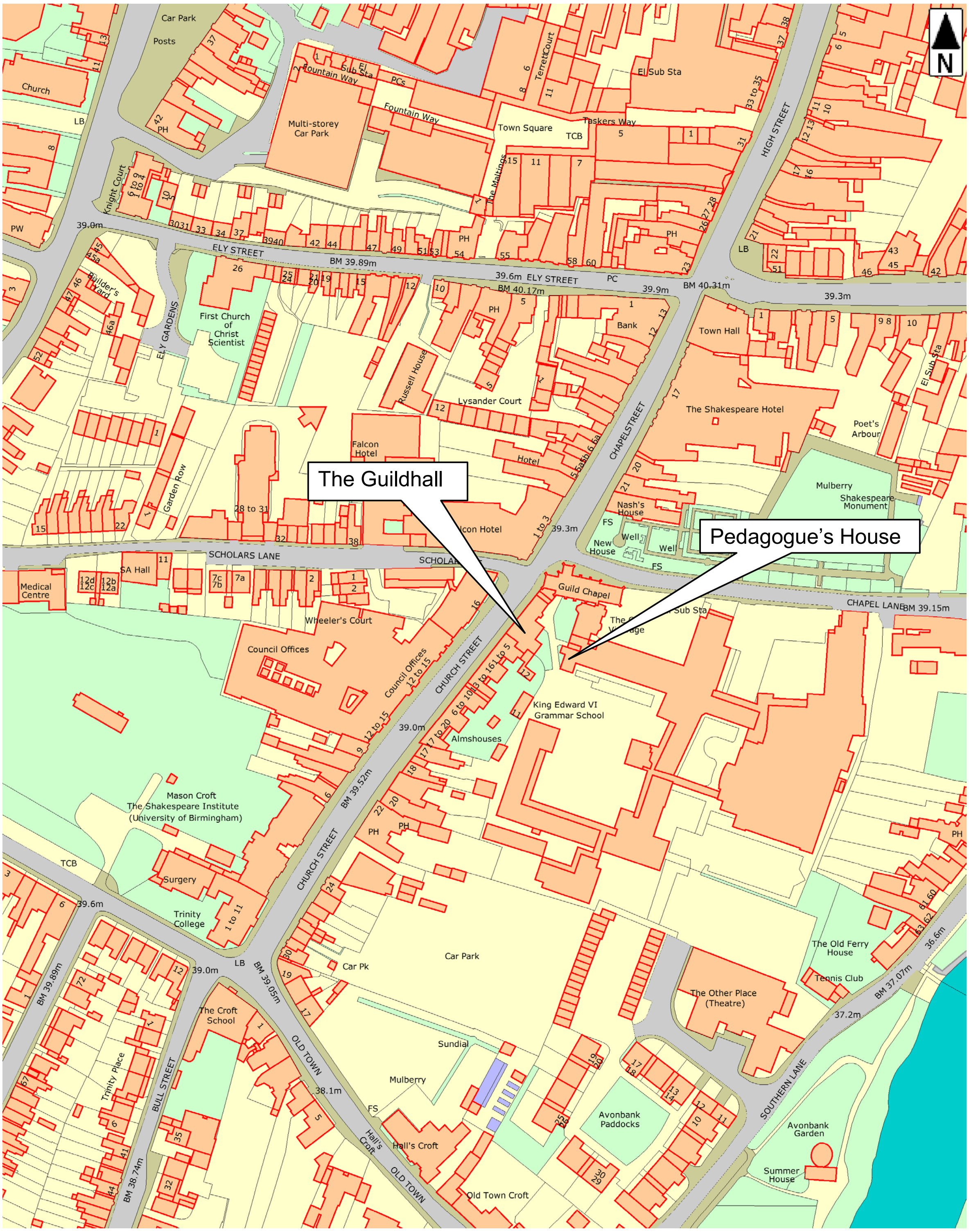

Figure 2: Map showing the specific location of The Guildhall and Pedagogue's House, Stratford-upon-Avon. This map is based upon Ordnance Survey material with the permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office. © Crown Copyright. Unauthorised reproduction infringes Crown Copyright and may lead to prosecution or civil proceedings. English Heritage. 100019088. © English Heritage

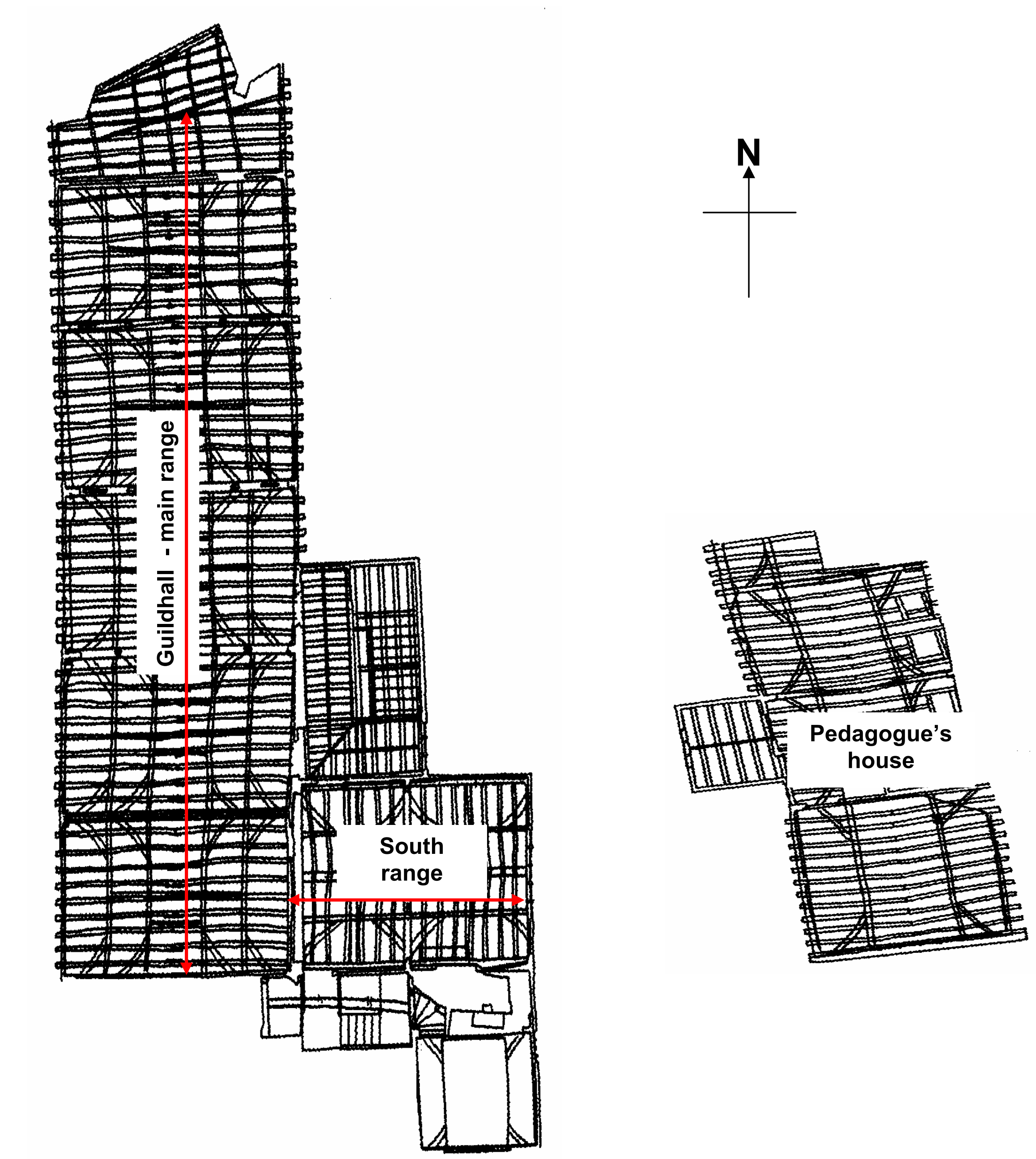

Figure 3: Simple plan to show the arrangement and layout of the buildings (after Field Archaeology Services, York, Ltd)

Figure 4a/b: View of the main and south ranges of the Guildhall (top, viewed from the south-east) and the south end of the Pedagogue's House (bottom, viewed from the south-west)

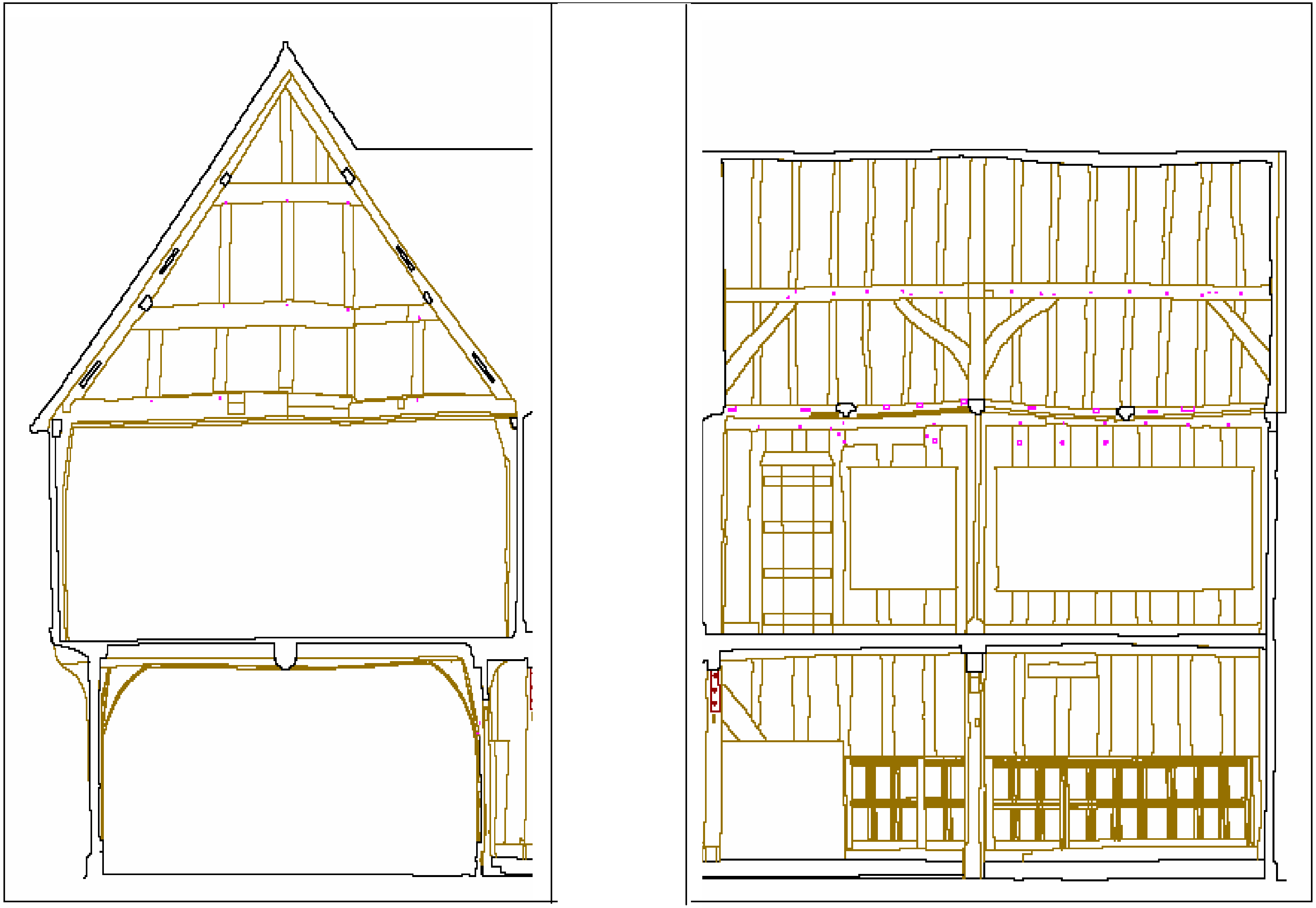

Figure 5a/b: Cross-section showing truss 5 of the main Guildhall range (to left) and long-section through the south range (to right – both viewed from the south looking north) (after Field Archaeology Specialist, York, Ltd)

Figure 6a/b: The Pedagogue's House; truss 1 (top), truss 3 (bottom) (viewed from the south looking north)

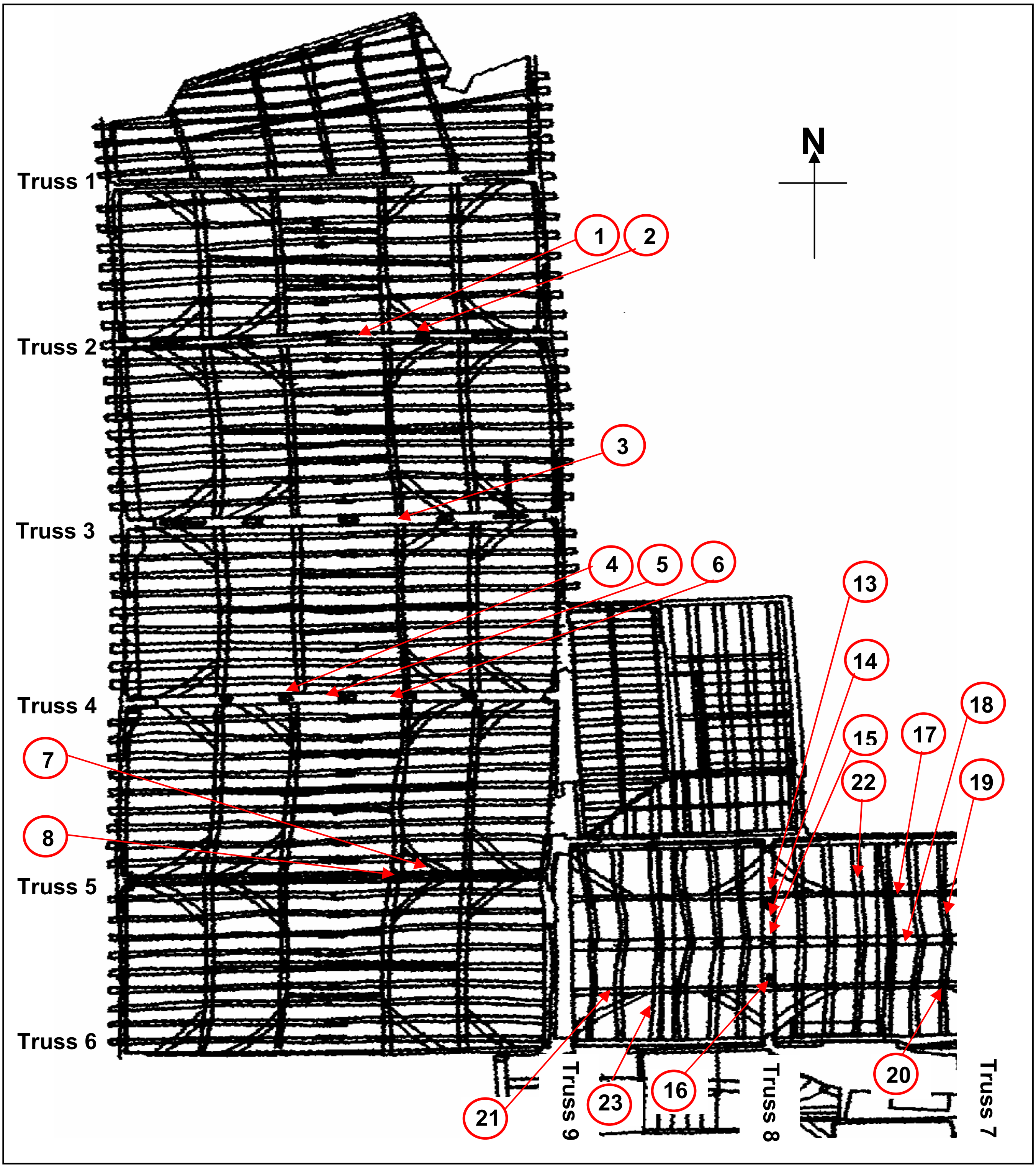

Figure 7a: Plan to show approximate location of samples from the roof of the main range of the Guildhall and the roof and ceiling of the south range (after Field Archaeology Services, York, Ltd)

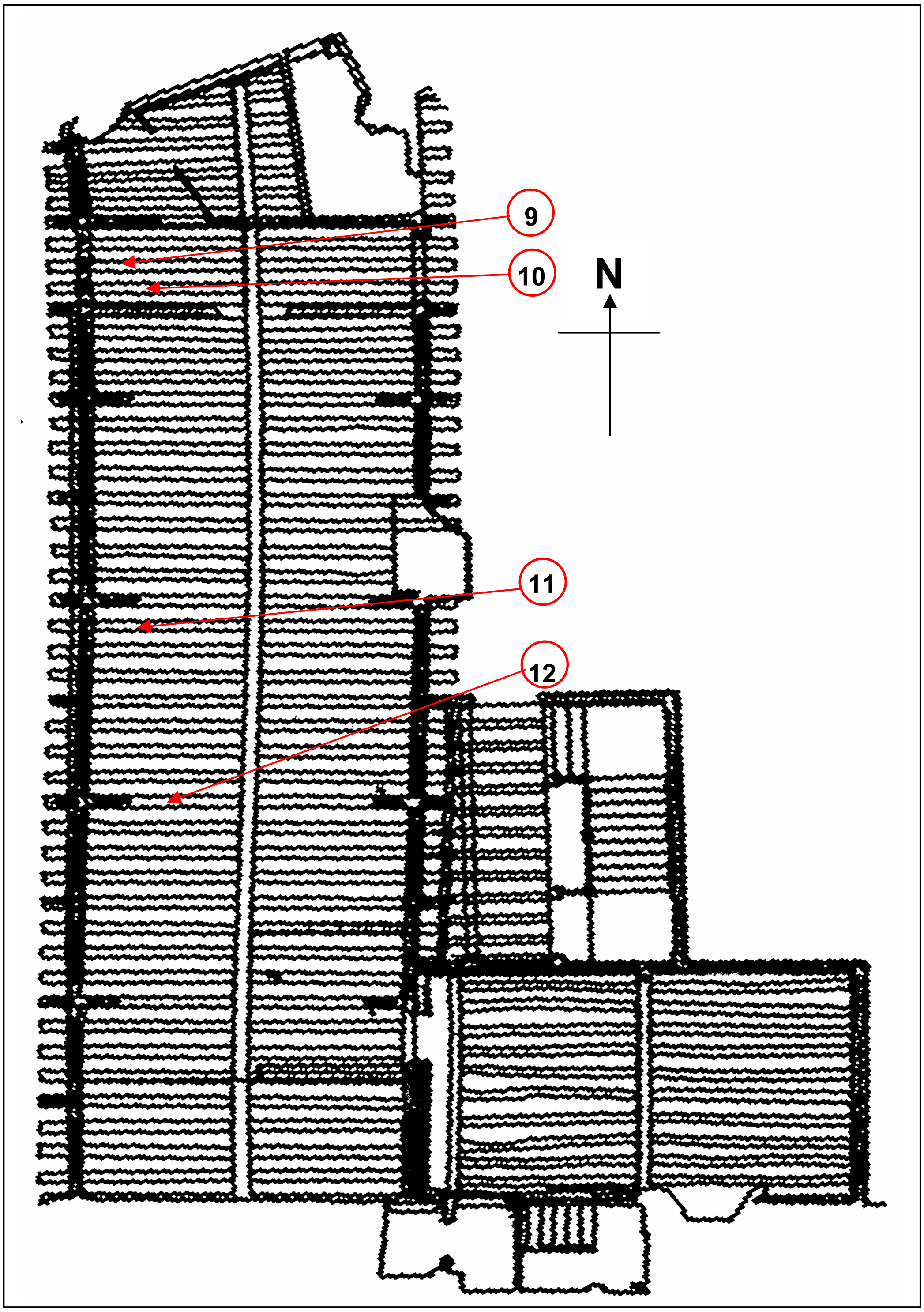

Figure 7b: Plan to show samples from the ground-floor ceiling of the main range of the Guildhall (after Field Archaeology Services, York, Ltd)

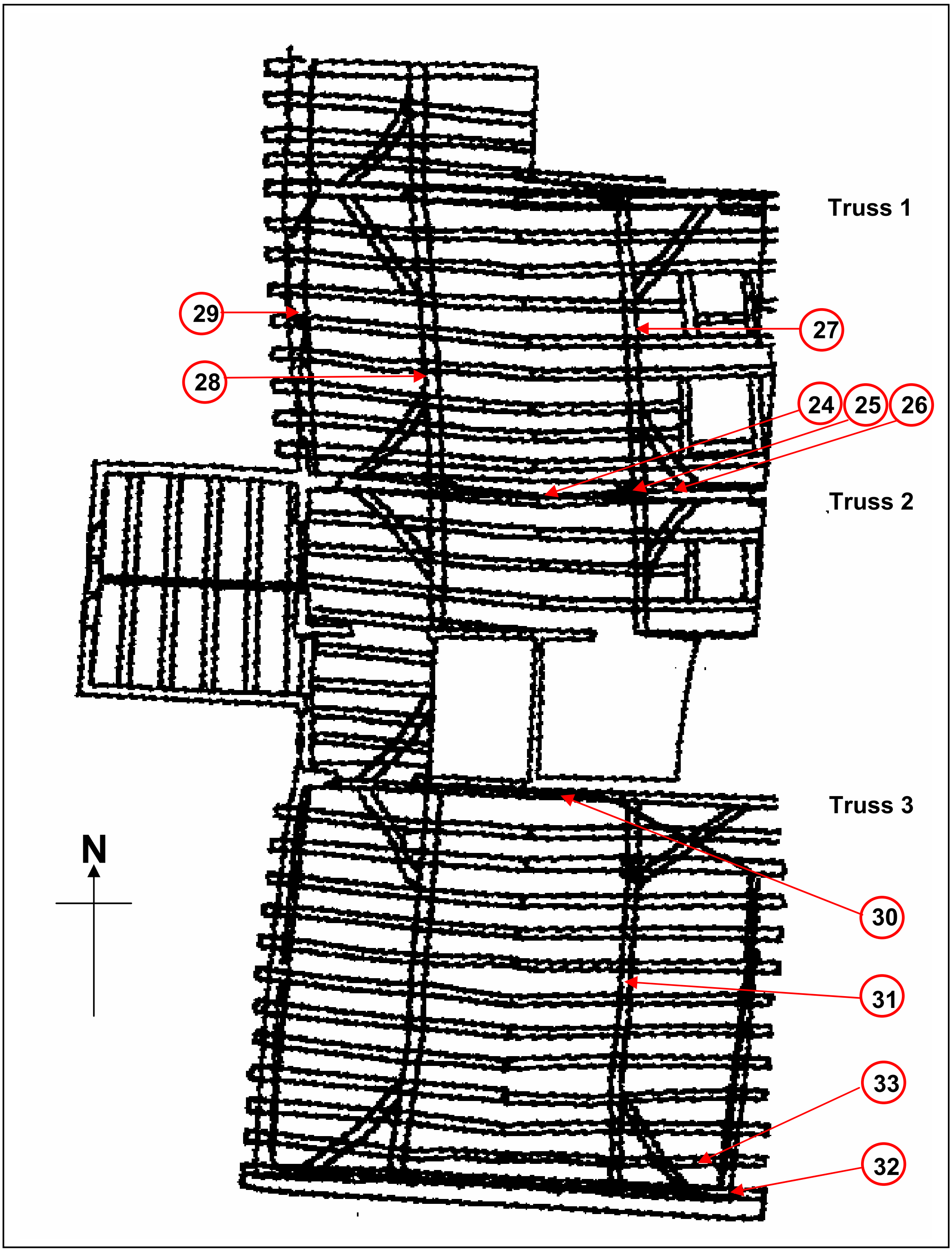

Figure 7c: Plan to show approximate position of samples from the Pedagogue's House (after Field Archaeology Services, York, Ltd)

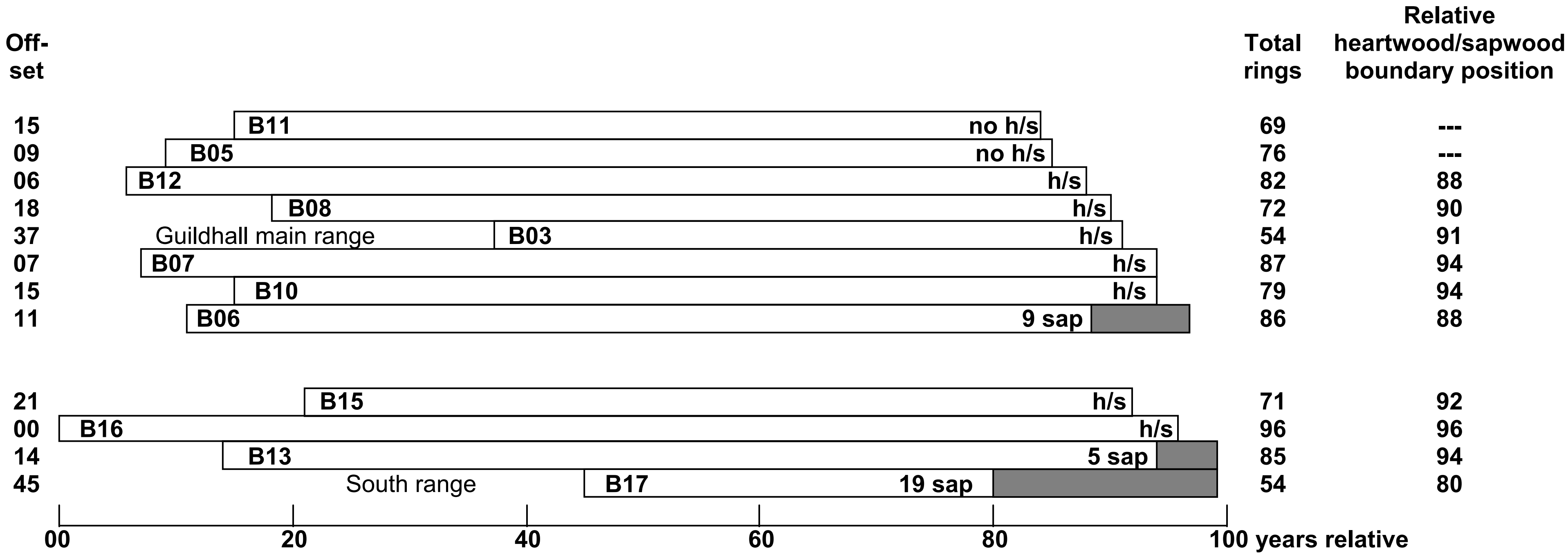

Figure 8: Bar diagram of the samples in site chronology SUABSQ01

white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary

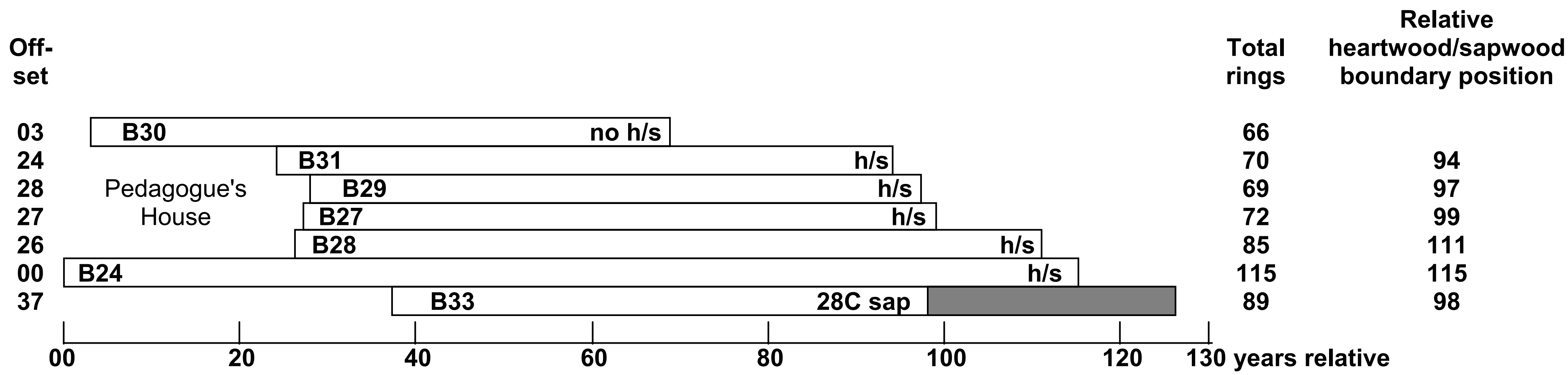

Figure 9: Bar diagram of the samples in site chronology SUABSQ02

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

Data of measured samples – measurements in 0.01 mm units

SUA-B01A 62
158 184 284 385 302 623 456 816 749 636 565 446 567 527 340 342 366 331 382 403
448 280 330 345 290 238 270 298 250 321 418 464 427 406 320 285 257 277 261 273
505 477 343 241 254 380 367 371 515 344 452 417 483 410 307 248 324 316 512 560
531 521
SUA-B01B 62
160 191 267 395 304 686 475 811 747 619 566 448 550 506 337 356 376 357 383 418
441 285 345 351 307 231 285 297 295 295 387 492 390 424 309 283 269 297 231 286
517 467 333 242 253 380 370 395 492 328 466 382 482 399 291 237 325 379 460 556
535 535
SUA-B03A 54
271 227 186 259 268 219 488 525 357 581 343 496 577 398 551 425 432 684 338 392
655 653 327 134 166 193 166 280 258 195 274 196 395 254 387 372 408 466 577 388
482 413 445 316 507 546 368 498 381 447 308 430 534 294
SUA-B03B 54
268 230 183 261 271 220 497 533 368 587 344 492 565 398 491 402 410 679 322 378
652 669 350 130 168 182 150 278 248 191 273 187 399 268 382 381 401 474 564 400
471 434 424 340 517 571 362 498 376 439 314 485 505 282
SUA-B04A 89
397 439 441 490 503 401 256 245 333 555 422 460 415 448 432 374 521 565 411 339
378 420 328 369 389 152 113 175 105 88 183 158 116 102 125 98 99 97 149 134
50 43 36 48 65 78 84 75 87 81 161 125 60 58 37 36 56 56 64 78
71 73 93 56 39 41 34 38 55 74 50 59 57 126 96 82 155 94 174 164
279 287 209 185 151 133 267 214 210
SUA-B04B 89
424 458 443 488 434 397 250 267 328 564 427 466 403 458 429 360 530 537 427 332
377 405 361 402 394 148 102 181 104 95 198 152 113 103 118 100 105 96 150 128
47 41 41 49 59 80 85 74 85 75 161 129 50 64 38 39 53 57 66 83
66 71 96 49 39 43 31 32 53 87 52 44 70 130 92 92 153 99 174 165
296 291 211 193 160 128 279 193 233
SUA-B05A 76
218 283 263 174 131 225 250 170 101 60 69 60 46 107 71 48 100 74 126 144
191 174 182 296 316 269 235 254 244 314 228 309 359 403 386 260 156 166 118 163
168 174 252 292 289 349 237 288 421 358 300 202 203 222 207 226 180 151 132 153
73 111 121 133 135 187 139 117 157 126 119 118 119 123 114 172
SUA-B05B 76
225 302 264 161 124 211 222 146 98 59 75 44 49 91 88 47 106 73 123 138
181 179 179 315 300 267 238 251 243 312 222 311 361 390 386 247 151 165 123 159
170 180 239 300 287 361 244 276 438 363 303 199 206 228 196 227 199 138 128 160
80 103 124 143 129 198 129 126 138 131 103 123 155 124 96 176
SUA-B06A 86
314 278 328 417 381 413 313 314 275 201 208 278 269 190 228 177 214 162 167 232
162 223 172 204 179 191 191 165 151 178 192 171 158 221 159 185 96 162 152 89
100 154 107 122 97 135 142 205 174 131 136 156 128 211 163 138 142 100 71 135
137 134 128 131 100 97 108 103 105 105 130 104 113 125 77 131 68 81 100 74
131 92 96 136 127 137
SUA-B06B 86
318 319 328 426 405 402 323 306 286 202 223 300 273 197 242 195 215 158 157 217
174 209 169 214 172 203 190 156 153 181 191 168 162 229 161 185 73 147 150 91
98 161 119 114 109 150 156 206 164 133 133 159 148 208 160 143 138 89 90 129
139 137 122 131 106 95 102 120 95 98 162 98 121 123 99 105 69 79 94 84
111 97 92 140 130 141
SUA-B07A 87
276 302 281 395 357 328 283 213 203 257 148 178 92 112 66 166 164 177 281 178
161 156 163 159 143 163 181 195 151 236 199 242 148 219 174 148 233 223 172 222
122 132 115 118 121 155 142 145 75 118 155 221 196 128 149 139 123 148 162 130
131 97 112 107 99 123 129 186 167 116 172 131 142 130 188 227 141 117 106 146
80 118 105 72 112 115 170
SUA-B07B 87
288 313 265 418 360 348 194 221 224 246 128 176 136 96 97 200 154 172 263 195
152 144 172 179 141 155 178 195 167 235 192 238 154 216 171 157 222 217 182 235
121 125 125 114 118 152 149 137 79 115 160 223 173 129 148 129 124 168 166 128
133 94 119 98 115 123 119 179 169 111 156 144 133 139 181 234 149 123 120 131
86 132 98 76 102 123 152

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SUA-B08A 72
233 216 140 137 250 249 242 232 170 161 238 235 267 202 222 241 212 208 234 290
184 190 267 259 201 238 185 102  89  70  98 124 157 177 158 155 146 124 125 104
168 106  86 104 132 114 158 113  81 117  57 111 165 196 188 199 188 172 155 182
223 174 147 158 129 173 163 145 131 122 131 171
SUA-B08B 72
234 200 155 152 238 269 262 185 149 159 234 238 264 201 235 243 222 205 240 306
159 203 249 259 208 240 184 104  95  74  88 132 150 177 154 137 145 121 140 119
153 106  92 101 125  98 147 111  82 104  67 100 169 179 192 203 196 157 164 188
227 174 139 163 123 161 169 151 122 121 146 167
SUA-B10A 79
248 165  99  70 106  59  56 109 163 250 289 205 345 343 306 379 270 418 290 321
263 391 334 399 374 378 307 271 433 364 227 281 222 317 271 194 185 244 274 296
161 157 333 275 206 216 215 192 130 151 124  79  63  47  77  95 106 153 126 156
145 118 116  83 137 101 140 132 145 122  92 129  77  94 119  93 184 174 189
SUA-B10B 79
253 167  95  78 101  69  57 105 153 260 288 197 347 324 299 373 282 411 281 326
284 380 345 381 372 381 308 274 415 378 225 265 220 307 275 195 185 254 273 309
154 159 343 274 210 206 212 192 122 158 132  83  56  51  74  95 116 145 129 156
147 120 104  89 128 108 145 129 137 124  97 129  82  96 123  96 191 169 195
SUA-B11A 69
280 275 285 286 270 160 225 405 262 220 261 185 266 271 281 367 257 324 294 246
234 277 251 216 208 223 211 183 195 296 172 202 123 122 137 120 128 124 133 188
129 120 169 151 140 137 158 142 101 149 161 123  65  68  91 108 110 128 135 157
124 124 156 124 152 112 142 146 137
SUA-B11B 69
343 250 279 322 292 187 231 389 284 232 248 181 272 284 295 429 253 319 307 246
215 270 239 229 209 227 221 181 208 293 168 198 120 119 144 109 102 121 146 169
123 114 174 150 157 131 140 131 121 155 157 110  74  71  97  99 123 121 131 156
127 119 162 126 138 133 134 151 137
SUA-B12A 82
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105  81 106 189 168 138 108 134 165 169 174 150 149 147 243 183 193 247 141 106
107 149 189 150 114 109  80  67  72  84 141 134 255 247 137 101 109 135 171 123
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131 124
SUA-B12B 82
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103  88  98 188 170 128 129 131 164 159 159 164 152 163 221 181 196 238 150  94
120 153 175 142 102 116  72  71  52  92 144 137 289 257 134 107 107 126 163 133
114  56  47  38  72  52  66  70  78  70  71  77  80  95 108 117  93  96  71  78
112 125
SUA-B13A 85
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334 250 367 270 217 176 255 263 213 291 354 187 244 209 488 466 227 178 229 220
235 146 175 315 280 275 197 173 152 153 281 218 137 144 116 125 151 149 181 195
165 145 140 146 172 179 136 198 159 136 142 121 132 120 109 120  86 142 141 159
177 202 168 160 191
SUA-B13B 85
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295 257 372 267 231 184 262 270 230 299 339 179 252 198 461 455 225 174 230 222
240 161 167 315 295 277 185 166 166 147 280 216 140 142 114 124 154 148 193 187
164 148 133 159 152 194 140 185 174 133 128 126 139 106 119 119  92 142 140 157
179 194 168 160 189
SUA-B14A 54
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241 261 257 205 172 200 182 237 280 332 321 358 274 269
SUA-B14B 54
256 389 431 290 346 397 390 310 320 261 215 160 215 229 291 214 181 192 172 178
 97  48  40  39  52  48  29  37  60  74 141 144 162 204 256 212 223 350 351 377
257 266 267 187 160 207 184 235 263 341 323 348 273 266
SUA-B15A 71
181 275 196 205 262 121 235 208 225 263 254 243 275 241 195 210 160 132 105 173
144 102 162 123  81  92  96 109  65  42  49  34  32  42  40  60  69  83  73  65
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SUA-B15B 71
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38 46 38 52 27 20 25 39 28 27 28 26 32 36 45 29 29 43 59 47
47 59 55 41 47 53 40 46 60 58 66
SUA-B16A 96
278 287 297 330 274 268 199 303 169 242 310 248 252 213 263 273 242 281 306 219
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220 163 106 165 144 143 142 130 157 122 79 79 102 66 92 69 83 136 130 97
73 81 68 55 83 57 40 63 63 47 44 38 49 42 65 42 34 43 62 60
54 66 61 46 53 56 65 47 73 85 65 79 91 99 157 177
SUA-B16B 96
310 269 327 355 272 261 210 292 178 247 298 282 271 233 271 250 305 290 321 229
157 137 223 236 168 199 136 217 172 167 198 175 167 180 205 143 198 143 128 115
232 141 112 158 159 136 132 127 165 114 72 85 91 74 90 76 84 129 119 88
82 77 66 58 82 53 50 58 55 51 50 33 50 54 45 41 40 51 58 64
47 67 75 64 44 53 69 43 78 82 56 91 82 114 150 185
SUA-B17A 54
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229 162 150 138 112 124 126 156 175 212 149 140 146 122 115 103 146 163 117 114
111 102 87 106 131 120 119 140 172 225 129 178 115 140
SUA-B17B 54
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227 173 167 146 118 115 133 147 174 220 151 138 143 123 119 108 136 160 141 131
110 102 84 110 122 105 135 141 172 202 159 174 132 159
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187 181 161 291 245 188 141 123 116 164 139 119 180 146 107 162
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352 226 258 353 381 396 314 329 248 245 237 190 197 180 183 124 102 130 169 166
179 195 159 304 243 185 130 128 120 160 137 124 170 152 107 163
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172 164 162 190 218 150 178 181 219 275 171 155 198 323 291 193 260 189 282 137
98 72 60 94 90 93 137 115 161 117 149 169 112 124 140 161 258 125 161 186
130 115 118 160 197 210 105 151 176 161 219 204 316 141 188 293 210 134 155 163
SUA-B19B 80
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151 157 171 192 217 154 175 182 220 278 173 150 203 313 301 196 254 197 278 116
101 79 51 104 87 96 135 120 156 116 151 172 116 122 152 158 274 118 162 181
134 111 119 162 213 217 100 142 188 156 213 215 311 137 200 290 203 151 152 161
SUA-B24A 115
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269 390 290 373 346 278 327 430 215 137 185 165 193 196 131 173 211 138 124 123
146 278 204 212 175 198 253 264 199 144 171 183 171 94 82 71 61 66 59 63
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104 95 97 95 87 92 79 38 52 49 43 52 47 36 50 57 52 79 64 83
62 46 69 82 105 95 103 110 86 74 90 82 83 101 104
SUA-B24B 115
241 154 370 421 142 123 138 170 232 275 310 344 352 458 548 411 388 262 211 325
280 388 290 378 337 264 323 431 201 126 170 162 206 186 132 173 203 143 134 114
150 287 198 201 180 202 255 268 198 147 156 193 173 109 64 70 53 62 58 59
53 61 53 72 130 126 118 110 86 87 108 85 79 97 100 108 84 70 109 115
99 103 83 113 82 95 72 34 49 50 56 54 48 42 50 56 52 61 75 78
55 49 66 75 113 91 100 104 87 74 81 84 87 109 111
SUA-B25A 54
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401 386 325 292 232 252 261 205 132 176 148 134 255 220 257 245 205 182 167 142
153 184 193 237 264 218 179 172 183 202 189 224 224 147
SUA-B25B 54
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399 382 324 278 252 248 225 208 138 190 152 128 253 213 255 226 204 170 171 151
149 175 195 236 261 217 182 169 197 190 200 222 219 148
SUA-B27A 72
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340 293 218 187 156 179 105 144 183 145 81 110 63 65 68 66 99 115 108 99
120 107 95 100 98 133 125 139 93 133 119 116 113 135 169 121 167 136 127 129
84 108 87 122 138 103 90 97 112 158 132 146

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SUA-B27B 72
147 243 248 237 306 271 227 172 183 174 144 107 116 143 221 178 334 228 198 277
335 288 221 193 154 176 108 125 195 134  91 111  70  58  65  67  95 116 103  96
113 109  96  98 113 128 101 125  81 140 114 104 118 134 166 123 166 122 125 119
 89  95  86 106 138 101  82 113 107 155 129 141
SUA-B28A 85
264 234 203 229 229 250 267 184 206 240 206 254 189 214 187 186 126 198 186 132
206 144 200 130 182 176 117 110 120 149 103 123 106  90  51  38  54  75 126  72
110 168 102  77  84  98 122 130 196 185 171 134 175 165 151 177 164 199 152 167
176 129 139 150 135 196 165 126 119 132 126 266 359 278 150  97  66 119 120 106
104  80 155 117 144
SUA-B28B 85
242 235 184 249 224 243 271 182 203 248 214 248 184 216 197 188 107 220 207 128
228 154 196 144 183 178 140 113 119 152  99 118 115  81  56  30  53  76 120  76
108 158 121  77  91  87 120 129 193 200 155 133 165 170 152 173 169 201 149 171
180 122 145 153 134 187 161 116 122 123 127 263 359 278 175  99 100 107 133 124
108  85 147 126 143
SUA-B29A 69
227 305 312 203 225 128 120 145 119 144 109  99 109 108 114 202 186 143 186 236
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216 189 166 146 143 142 177 136 147 119 140 114 111 108  95 107 106 111 109  73
 78  95  90  75  72  64  60  72  96
SUA-B29B 69
236 312 215 257 211 136 113 167 114 133 113  95 109 131 119 166 229 145 190 228
280 184 200 132 115 147 159 180 156 169 143 155 150 152 153 145 219 167 248 300
209 190 181 149 149 150 171 132 156 117 131 124 108 101  94 117  91 117 109  71
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SUA-B30A 66
158 330 383 171 180 266 375 278 248 188 259 237 264 243 141  90 128 168 287 334
402 329 228 231 300 161 163 172 149 148 132 153 141 153  95  78  92 104 151 116
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135 142 133 135  96  95
SUA-B30B 66
162 332 341 192 205 295 355 256 233 165 235 248 266 236 176 103 146 186 302 337
398 328 220 233 295 173 157 172 158 141 133 156 137 149 102  68 106  94 159 118
161 130 153 131 148 136  88 112 146 155 126 126 164 142 109 161 130 137 142 104
114 161 135 125 100  98
SUA-B31A 70
273 245 291 277 191 188 151 168 200 151 166 179 136 101  86 127  94 118  95 214
173 160 205 178 230 135 176 127 119  88 124 137 108  76  48  34  33  36  33  35
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105 114 126 113  92  90  92 111  76  80
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168 160 170 171 206 136 169 142 107  93 117 140 111  70  58  33  29  34  28  41
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102 114 125 110  96  83  91 107  68  73
SUA-B33A 89
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  97 92  72  65  79 115 129 120 118 107  105 78  61  67 135 112 125  99 104 146
149 126 142 172 158 177 158 176 115
SUA-B33B 89
181 138 187 107 128 103 133 139  91 148 130 166 134 158 203 132 144 167 246 127
126 170  96  76  57  56  95 125  86 117 125  94 112 104  87  84  89  92  69  76
 66  81  82  65  82  83  94  88  79 121  65  78  84  65  64  65  60  51  47  60
 54 116  88  79  59  82 111 123 118 117 105  77  62  68 142 109 126  97 127 147
176 148 156 151 145 204 189 165 119
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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 measure twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

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	

Bar Diagram

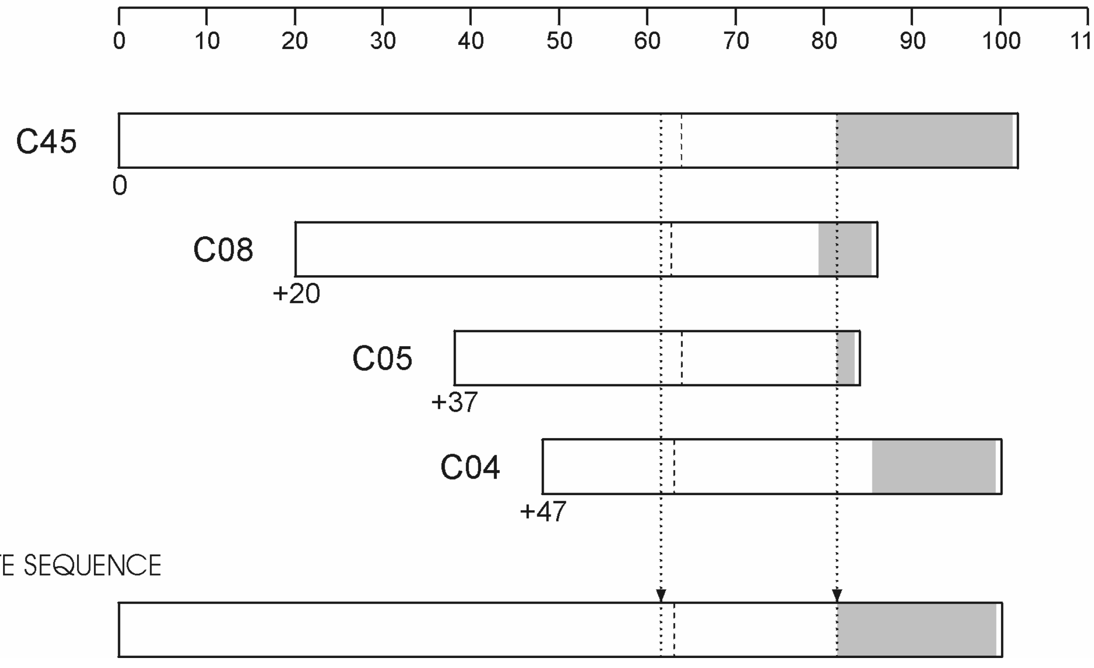

Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

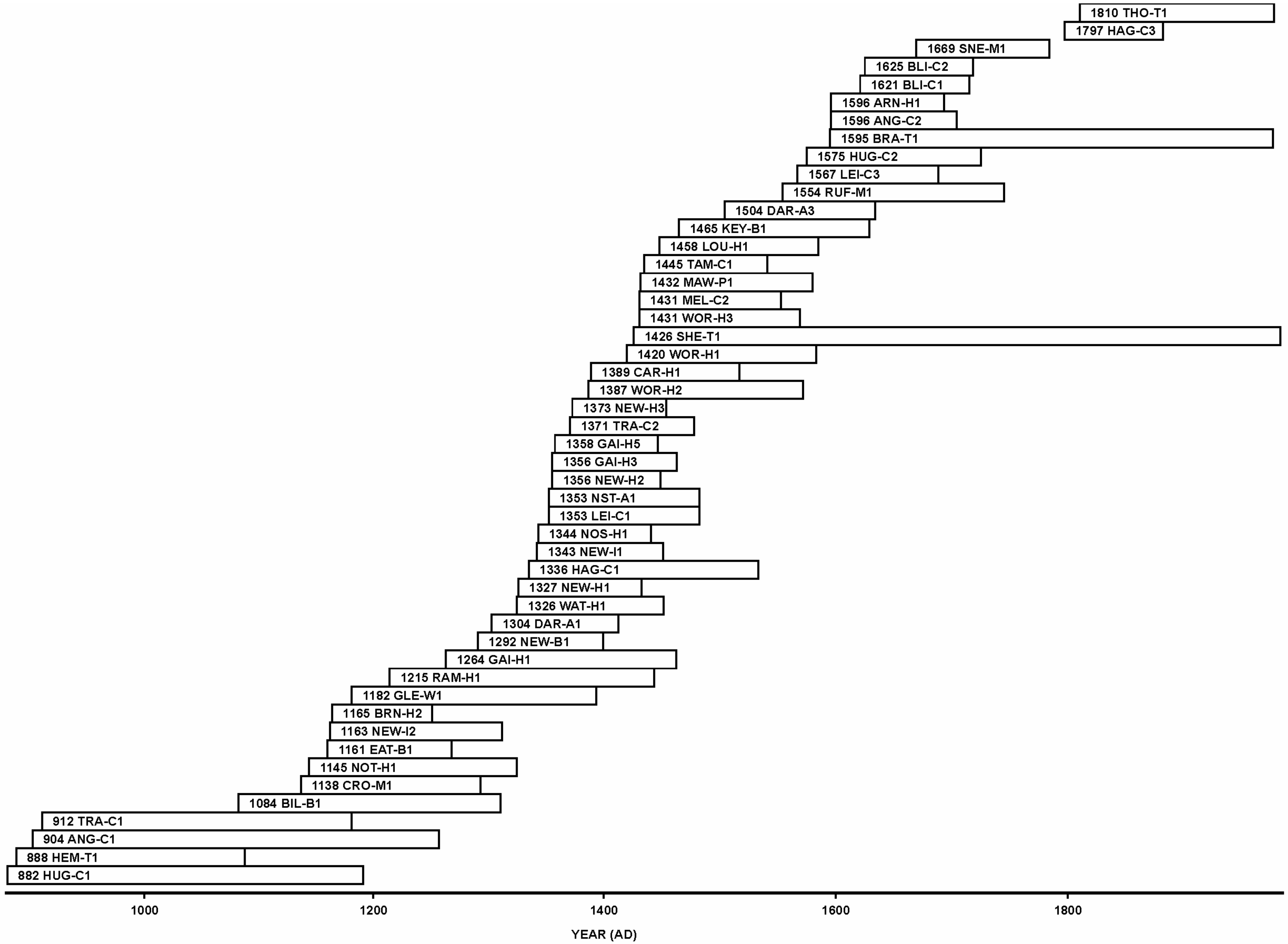

Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

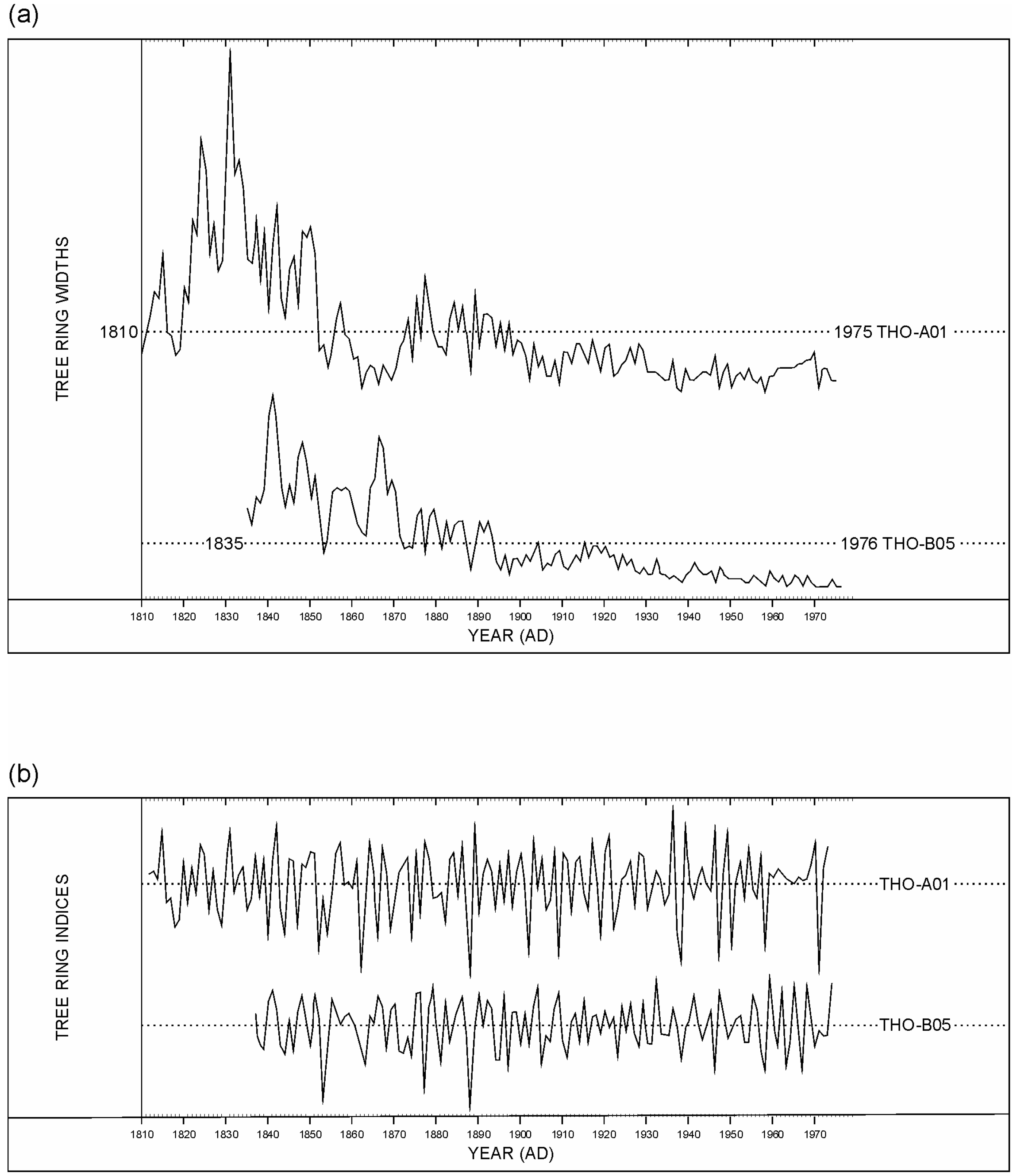

Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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