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Interpretation of the sapwood on the dated samples indicates that much of the material, particularly timbers from Floor S1, Roof S1/S2, Roof S3/S4, and a single timber from Floor S3, have an estimated felling date in the range AD 1699 - 1724. It is likely that such a felling date relates to the suspected late seventeenth-century remodelling.

However, there is some slightly earlier material with some further timbers from Floor S3 having an estimated felling date in the range AD 1590 - 1615. Timbers from Floor F6 appear to be possibly of two felling dates, one estimated as AD 1605 - 30, the other estimated as AD 1625 - 50.

There is no confirmed tree-ring evidence for any earlier material in any other part of the building, either original or reused.

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Keywords

Dendrochronology
Standing Building

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Introduction

Hulme Hall is the decayed remnants of the medieval Manor of Hulme, standing on an isolated and remote moated spot about three miles north of Northwich (SJ 724724; Figure 1). The hall was originally the seat of the Grosvenor family who came over from Normandy with William the Conqueror. They were to become a prominent Cheshire family in the Middle Ages. The family already owned land in Allostock when Richard Grosvenor acquired the Manor of Hulme from Graham de Lostock in AD 1234, and from then until AD 1465 it was their principal residence.

In AD 1465 the Manor was inherited by one of the Grosvenor daughters, who married John Legh of Booths. Their son, also named John Legh, likewise died without a direct male heir and the Manor was inherited by his daughter, Elizabeth, who married Peter Shakerley of Shakerley in Lancashire. His son, Geoffrey Shakerley, appears to have made the Manor of Hulme his residence early in the sixteenth century and it remained the principal seat of the Shakerley family for the better part of two hundred years.

Geoffrey Shakerley's grandson, also named Geoffrey Shakerley, was Sheriff of Cheshire in the reign of James I, and the latter's great-grandson, Sir Geoffrey Shakerley, fought on the Royalist side in the Civil War and was governor of Chester Castle. From the late-seventeenth century onwards, although Hulme Hall remained in the possession of the Shakerley family, they appear to have lived elsewhere and the Hall was presumably tenanted. It is believed, on the basis of stylistic interpretation of various floor-frame beams, that substantial internal alterations were made to the buildings in the late-seventeenth century. In the nineteenth century much of the hall was demolished with that which remained being encased in brickwork. The site is still accessed across the medieval stone bridge

The building, an outline plan of which is given in Figure 2, now comprise three principal blocks, an east and a west block connected by a central block. It is believed that each of these three blocks contains fabric dating to the seventeenth-century alteration phase, with some of the timbers possibly being earlier. For example, while the roofs of the central and east blocks appear to be made entirely of softwood, that of the west block appears, on the basis of the form of the framing, to retain its original oak timbers. The frames of the first and second floors of each block also appear, again judged on stylistic evidence, to be made of later, probably seventeenth-century, oak. In addition there are two nineteenth-century single-storey extensions which, judging by the evidence of redundant mortices, reuse oak beams as purlins. It is believed that these may be from other parts of the early hall demolished in the nineteenth century. In general, the survey of the building undertaken by Anthony Blacklay and Associated indicates the possible use of timbers of different periods.

The building has suffered in the past from a lack of maintenance and periodic bouts of vandalism. It is currently (AD 2003) in poor condition and boarded-up. Proposed mineral extraction from the adjacent brinefields also affects the grounds around the building. The new owners of the site, Ineos Chlor are prepared to carry out urgent repairs and are keen to find a viable use of the building. As part of this process Ineos Chlor have commissioned a condition survey and a schedule of works.

The building is presently grade II* listed and is on the English Heritage Buildings at Risk Register.

Sampling

Sampling and analysis by tree-ring dating were commissioned by English Heritage, the purpose of this being to provide a precise date for a number of elements of the hall. In particular samples were to be obtained from what were believed might be original, possibly sixteenth-century, timbers of the east block roof; and from first- and second-floor frames of each of the three blocks. Samples were also to be obtained from timbers, possibly originally sixteenth-century, reused as purlins in two nineteenth-century extensions, plus samples from the timbers of the main stairs.

Given the complicated and multi-element nature of the site, helpful direction was obtained from Anthony Blacklay, of Anthony Blacklay & Associates, Architects & Historic Buildings and Landscape Consultants of Nantwich, as to the possible phasing of each part of the building. Thus, on the basis of this advice and from the extensive number of timbers available, a total of eighty-one samples was obtained. Each sample was given the code ALS-A (for Allostock, site "A") and numbered 01 - 81. Timbers were selected on the basis of their having sufficient rings for suitable analysis, and, where possible, for having sapwood, or at least the heartwood/sapwood boundary.

In this respect it was notable that while many of the roof timbers did retain some sapwood, it, and in some cases even the heartwood, was severely decayed, rotted, and soft. This was no doubt in large measure due to their long-time exposure to water leaking through the roofs. On the other hand the floor joists, which were more protected, had been severely trimmed by the original carpenters, with much of the sapwood being removed at that time.

An attempt was made to obtain samples evenly distributed between each element of the building. However, this was not always possible. In some cases this was due to there being insufficient oak timbers in one room, but the main reason for the lack of samples was that the timbers appeared to have too few rings, ie, less than 54, for satisfactory analysis. The most notable absence from sampling is the case of the timbers reused as purlins in the nineteenth-century extensions.

Where possible the approximate locations of timbers sampled were recorded at the time of coring on drawings kindly provided by Anthony Blackley and adapted to show the approximate positions of individual beams. Unfortunately the drawings do not show individual floor or roof timbers. These drawings are reproduced here as Figures 3a - c. In the architects plans each room has been numbered and prefixed with the letters "G" for ground floor, "F" for first floor, and "S" for second floor. This location system has been followed in Table 1 where details of the samples are given. In this Table timbers are numbered and identified on a north-to-south, or east-to-west basis as appropriate. In some cases, as with floor-frames, the presence of larger bridging beams has been used to divide the frames up into sections or sides, again described north / south / central, etc, as appropriate. Using the drawings and Table 1 it should be possible to identify the general location of timbers sampled.

The Laboratory would to take this opportunity to thank Anthony Blacklay in particular for his invaluable help in deciphering the possible phasing of the building and for providing plans and drawings. We would also like to thank Peter Latham and Peter Downes of Ineos Chlor for their constant cooperation in accessing this difficult and dangerous building, and for their professional concern for site safety.

Analysis

Each of the eighty-one samples was prepared by sanding and polishing. At this point it was seen that one sample, ALS-A61, not only had very few rings, less than 30, but also had highly distorted rings and it was rejected. The widths of the annual growth-rings of the remaining eighty samples were then measured. The data of these measurements are given at the end of this report. The measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see appendix).

Given that a large number of samples had only just at the Laboratories usual minimum number of rings for satisfactory analysis, ie 54, the allowed overlap between them was reduced to 40 rings. At a minimum value of t=4.5 four separate groups of cross-matching samples could be formed. The cross-matching samples of each group were then combined with each other at their relative offset positions to form site chronologies ALSASQ01 - ALSASQ04.

Each site chronology was then compared with the other three and with the remaining ungrouped samples. There was, however, no further satisfactory cross-matching. Each site chronology was then compared with a full range of reference chronologies for oak. This indicated a date for two site chronologies only, ALSASQ01 and ALSASQ02.

All the ungrouped samples were then compared individually with a full range of reference chronologies. There was, however, no further satisfactory cross-matching and these samples must, therefore, remain undated.

The relative positions of the cross-matching samples are shown in the bar diagrams Figures 4 - 6. Given that the two dated site chronologies overlap with each and include material from the same locations, the samples they contain are illustrated in a single bar diagram, Figure 4. The two component site chronologies are displayed by colour code with the samples sorted by location.

This analysis is summarised below:

Site chronology	Number of samples	Number of rings	Date span
ALSASQ01	15	116	AD 1574 - 1689
ALSASQ02	7	101	AD 1510 - 1610
ALSASQ03	3	68	Undated
ALSASQ04	2	119	Undated
Ungrouped	53	---	Undated

Interpretation

The relative positions of the heartwood/sapwood boundaries on the ten samples in site chronology ALSASQ01 where it exists is very consistent, varying by only nine years from relative position 170 (AD 1680) on samples ALS-A67, A68, and A69, to relative position 179 (AD 1689) on sample ALS-A49. Such consistency is indicative of timbers having a very similar, if not identical, felling date. The average heartwood/sapwood boundary date of the ten samples in site chronology ALSASQ01 where it exists is AD 1684. Using a 95% confidence limit for the amount of sapwood on mature oaks in this part of England of 15 - 40 rings would give the timbers represented by these samples an estimated felling date in the range AD 1699 to AD 1724.

The relative positions of the heartwood/sapwood boundaries of the four samples in site chronology ALSASQ02 where it exists is more variable, the difference between earliest and latest being 38 years. Such a variation suggests that timbers were felled at different times.

The earliest heartwood/sapwood boundaries are found on samples ALS-A72 and A73, at relative positions 62 and 67, AD 1572, and AD 1577, respectively. This is a variation of only five years and again may be indicative of a group of timbers having a single felling date. If this were assumed to be the case, the average last heartwood ring date of the two would be AD 1575. Using a 95% confidence limit for the amount of sapwood on mature oaks in this part of England of 15 - 40 rings would give the timbers represented by these samples an estimated felling date in the range AD 1590 to AD 1615.

The next heartwood/sapwood boundary in site chronology ALASQ02 is found on sample ALS-A21, this being at relative position 80, AD 1590. Using the same confidence limit for the amount of sapwood as above would give the timber represented by this sample an estimated felling date in the range AD 1605 to AD 1630.

The latest heartwood/sapwood boundary of any sample in site chronology ALSASQ02 is found at relative position 100 on sample ALS-A14, AD 1610. Using the same confidence limit for the amount of sapwood as above would give the timber represented by this sample an estimated felling date in the range AD 1625 to AD 1650.

Conclusions

Analysis by tree-ring dating has produced four site chronologies from the material obtained at Hulme Hall. Only two of these, site chronology ALSASQ01 comprising fifteen samples and being of combined overall length 116 rings, and site chronology ALSASQ02 comprising seven samples, of combined overall length 101 rings, are dated, spanning the years AD 1574 to AD1689 and AD 1510 to AD 1610 respectively.

Interpretation of the sapwood on the samples in site chronology ALASQ01 indicates that many of the dated timbers were cut in a single phase of felling estimated to have taken place sometime between AD 1699 - AD 1724. It will be noted from Table 1 and the bar diagram Figure 4 that much of this dated material is from the roof and floor-frames of rooms S1 - S4, suggesting that this area contains the greatest quantity of early eighteenth-century material.

Such a date is probably related to the believed seventeenth-century refurbishment phase, though on the basis of tree-ring dating, it is more likely to have taken place in the early eighteenth century. The tree-ring analysis shows no evidence at all of any earlier material from the central or western area of the building, either in its original position or reused.

Earlier phases of felling are, however, also present, being represented in site chronology ALASQ02. It is estimated, for example, that two timbers from Floor S3 (samples ALS-A72 and A73) have a felling date in the range AD 1590 to AD 1615. Additional felling dates within Floor F6 may also be represented in site chronology ALSASQ02. One timber, represented by sample ALS-A21, has an estimated felling date in the range AD 1605 to AD 1630. It is possible, however, that these three samples (ALS-A21, A72, and A73) were felled at the same time in the period AD 1605 to AD 1615, where the estimated felling date range of each overlap.

The other timber, represented by sample ALS-A14, has an estimated felling date in the range AD 1625 to AD 1650. Again, though, given that there is a slight overlap in the felling date ranges of these last two samples (ALS-A14 and A21), it is possible that they share a felling date in the range AD 1625 - 30.

It would thus appear that, as suspected during the survey of the building by Anthony Blacklay, timbers of different dates and possibly from different sources appear to have been used.

The measured samples from some fifty-three other timbers, an extremely high proportion, cannot be dated, despite every effort to do so. The most likely reason for this is the low number of annual rings on several of the cores. The majority of undated samples have only 54 rings, the minimum number for satisfactory analysis. A number of others undated samples have only 55 - 60 rings. Only ten undated samples have more than 60 rings. The low numbers of rings on the samples make satisfactory cross-matching, and the reliable dating of individual samples, very difficult if not impossible.

A number of the undated samples also show bands of narrow or distorted rings. These bands may be caused by stress, or some non-climatic influence such as pollarding or the stripping of leaves. This would have the effect of making the growth pattern of the samples incomparable with the reference patterns.

A further possible contributory factor in the lack of dating may be the widespread use of timbers with various felling dates in the sixteenth and seventeenth centuries, and possibly from different sources. Tree-ring dating tends to be more effective where groups of homogeneous timbers are sampled. In this instance the timbers may be too varied for complete success.

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Table 1: Details of samples from Hulme Hall, Allostock, Cheshire

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Floor-frame to room F5					
ALS-A01	Main north – south beam	71	h/s	------	------	------
ALS-A02	West joist 7	54	h/s	------	------	------
ALS-A03	West joist 2	55	no h/s	------	------	------
ALS-A04	East joist 11	54	no h/s	------	------	------
ALS-A05	West common rafter 3	69	h/s	------	------	------
ALS-A06	East common rafter 10	54	h/s	------	------	------
ALS-A07	East common rafter 12	55	h/s	------	------	------
	Floor-frame to room F4					
ALS-A08	Joist 4	56	h/s	------	------	------
ALS-A09	Joist 1	55	h/s	------	------	------
ALS-A10	Joist 3	54	h/s	------	------	------
ALS-A11	Joist 5	57	h/s	------	------	------
ALS-A12	Joist 2	56	h/s	------	------	------
	Floor-frame to room F6					
ALS-A13	Main east-west beam	58	h/s	------	------	------
ALS-A14	Northern cross-beam	68	h/s	AD 1543	AD 1610	AD 1610
ALS-A15	South joist 2	54	no h/s	------	------	------
ALS-A16	North joist 8	54	no h/s	------	------	------
ALS-A17	South joist 4	60	h/s	------	------	------

Table 1: continued

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Floor-frame to room F6 continued					
ALS-A18	North joist 9	55	no h/s	AD 1546	------	AD 1600
ALS-A19	South joist 6	59	no h/s	AD 1510	------	AD 1568
ALS-A20	North joist 10	70	no h/s	AD 1513	------	AD 1582
ALS-A21	South joist 3	67	h/s	AD 1524	AD 1590	AD 1590
ALS-A22	South joist 5	55	h/s	------	------	------
	Floor-frame to room F3					
ALS-A23	East joist 3	70	h/s	------	------	------
ALS-A24	East joist 4	56	h/s	------	------	------
ALS-A25	West joist 6	54	h/s	------	------	------
ALS-A26	West joist 2	57	h/s	------	------	------
ALS-A27	West joist 5	65	h/s	------	------	------
ALS-A28	East joist 2	58	h/s	------	------	------
ALS-A29	Common joist 2 from east side	87	h/s	------	------	------
ALS-A30	Western north -south bridging beam	54	h/s	------	------	------
ALS-A31	North wall plate at east side	57	h/s	------	------	------
ALS-A32	Joist 3 east side, mid section	56	3	------	------	------
ALS-A33	Joist 2, east side, mid section	54	h/s	------	------	------
ALS-A34	Joist 5, east side, south section	54	h/s	------	------	------

Table 1: continued

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Floor-frame to room F1					
ALS-A35	Joist 1, east side	57	h/s	------	------	------
ALS-A36	Joist 3, west side	57	h/s	------	------	------
ALS-A37	Joist 2, mid section	54	h/s	------	------	------
ALS-A38	Joist 4, west side	55	h/s	------	------	------
ALS-A39	Joist 1, west side	59	h/s	------	------	------
ALS-A40	Joist 5, east side	54	h/s	------	------	------
	Roof to room S3 / S4					
ALS-A41	East upper purlin, S3	54	h/s	------	------	------
ALS-A42	Ridge beam (S3 - S4)	58	h/s	------	------	------
ALS-A43	East middle purlin, S3	69	no h/s	AD 1594	------	AD 1662
ALS-A44	West upper purlin, S4	60	h/s	------	------	------
ALS-A45	East common rafter 7, S3	54	h/s	------	------	------
ALS-A46	West middle purlin, S4	54	h/s	------	------	------
ALS-A47	East lower purlin, S3	82	h/s	AD 1605	AD 1686	AD 1686
ALS-A48	West lower purlin, S4	54	h/s	------	------	------
ALS-A49	East lower purlin, S2	75	h/s	AD 1615	AD 1689	AD 1689
	Roof to room S1 / S2					
ALS-A50	West lower purlin, S1	103	no h/s	AD 1574	------	AD 1676
ALS-A51	West middle purlin, S2	55	h/s	------	------	------

Table 1: continued

Sample no	Sample location	Total Rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Roof to room S1 / S2 continued					
ALS-A52	East middle purlin, S2	76	h/s	AD 1613	AD 1688	AD 1688
ALS-A53	East upper purlin, S2	54	h/s	------	------	------
ALS-A54	Ridge beam, S1 / S2	55	h/s	------	------	------
ALS-A55	West middle purlin, S1	54	h/s	------	------	------
ALS-A56	East common rafter 9, S2	56	h/s	------	------	------
ALS-A57	West upper purlin, S1	98	h/s	AD 1585	AD 1682	AD 1682
ALS-A58	East common rafter 10, S2	66	h/s	AD 1619	AD 1684	AD 1684
ALS-A59	West common rafter 7, S1	86	no h/s	AD 1582	------	AD 1667
ALS-A60	East common rafter 7, S2	57	h/s	------	------	------
ALS-A61	West common rafter 2, S1	nm	h/s	------	------	------
	Floor-frame to room S1					
ALS-A62	Joist 8, centre section	55	h/s	------	------	------
ALS-A63	Joist 6, west section	54	h/s	------	------	------
ALS-A64	Joist 7, centre section	55	no h/s	AD 1588	------	AD 1642
ALS-A65	Joist 6, centre section	54	h/s	------	------	------
ALS-A66	N-S beam, west section	69	h/s	AD 1616	AD 1684	AD 1684
ALS-A67	Joist 2, west section	54	h/s	AD 1627	AD 1680	AD 1680
ALS-A68	N-S beam, east section	90	h/s	AD 1591	AD 1680	AD 1680
ALS-A69	Joist 3, east section	54	h/s	------	------	------
ALS-A70	Joist 7, west section	61	h/s	AD 1620	AD 1680	AD 1680
ALS-A71	Joist 5, east section	55	h/s	AD 1630	AD 1684	AD 1684

Table 1: continued

Sample no	Sample location	Total Rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Floor-frame to room S3					
ALS-A72	Joist 2, east side	54	h/s	AD 1519	AD 1572	AD 1572
ALS-A73	Joist 4, east side	47	h/s	AD 1531	AD 1577	AD 1577
ALS-A74	Central north – south beam	57	h/s	------	------	------
ALS-A75	Joist 6, east side	92	h/s	------	------	------
ALS-A76	Joist 5, west side	88	no h/s	AD 1585	------	AD 1672
	Stair timbers					
ALS-A77	Rail beneath stairs, ground floor	56	h/s	------	------	------
ALS-A78	Top newel post, first floor	54	h/s	------	------	------
ALS-A79	Middle rail to stair, first floor	62	h/s	------	------	------
ALS-A80	Middle newel post (lower part)	55	h/s	------	------	------
ALS-A81	Middle newel post (upper part)	84	h/s	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample

Table 2: Results of the cross-matching site chronology ALSASQ01 and relevant reference chronologies when the date of the first ring is AD 1574 and its last ring date is AD 1689

Reference chronology	Span of chronology	*t*-value	
Bolsover Castle, Derby (Riding house)	AD 1494 – 1744	8.9	(Howard *et al* forthcoming)
Bretby Hall, Bretby, Derbys	AD 1494 – 1718	6.7	(Howard *et al* 1999)
England	AD 401 – 1981	6.4	(Baillie and Pilcher 1982 unpubl)
East Midlands	AD 882 – 1981	6.4	(Laxton and Litton 1988)
Blidworth Church, Blidworth, Notts	AD 1621 – 1713	6.1	(Laxton and Litton 1988)
England London	AD 413 – 1728	5.9	(Tyers and Groves 1999 unpubl)
Sinai Park, Staffs	AD 1227 – 1750	5.7	(Tyers 1997)
Brewhouse Yard, Nottingham	AD 1544 – 1701	5.2	(Howard *et al* 1994)

Table 3: Results of the cross-matching site chronology ALSASQ02 and relevant reference chronologies when the date of the first ring is AD 1510 and its last ring date is AD 1610

Reference chronology	Span of chronology	*t*-value	
Dovebridge, Derbys	AD 1502 – 1617	6.1	(Howard *et al* 1998 unpubl)
Keyworth Barn, Keyworth, Notts	AD 1451 – 1528	5.4	(Laxton and Litton 1988)
East Midlands	AD 882 – 1981	5.3	(Laxton and Litton 1988)
Long Clawson, Leics	AD 1485 – 1602	5.3	(Howard *et al* 1991)
Hallfield House, Bradfield, S Yorks	AD 1482 – 1592	5.2	(Howard *et al* 1996)
England	AD 401 – 1981	5.2	(Baillie and Pilcher 1982 unpubl)
Frith Hall, Brampton, Derbys	AD 1480 – 1602	5.1	(Howard *et al* 1993)
Wales and West Midlands	AD 1341 – 1538	4.8	(Siebenlist-Kerner 1978)

Figure 1: Map to show general location of Hulme Hall

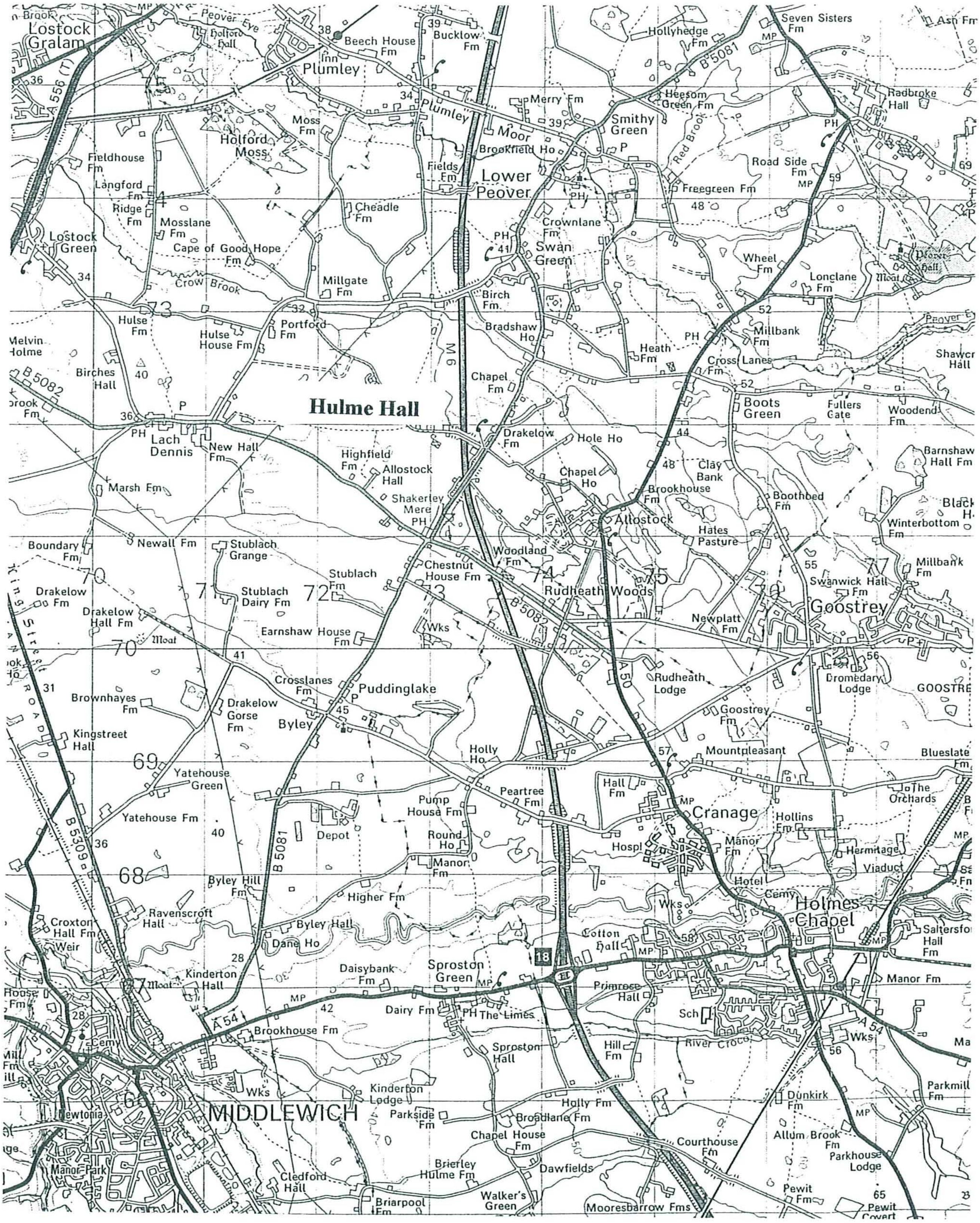


Figure 2: General layout of Hulme Hall based on ground floor plan

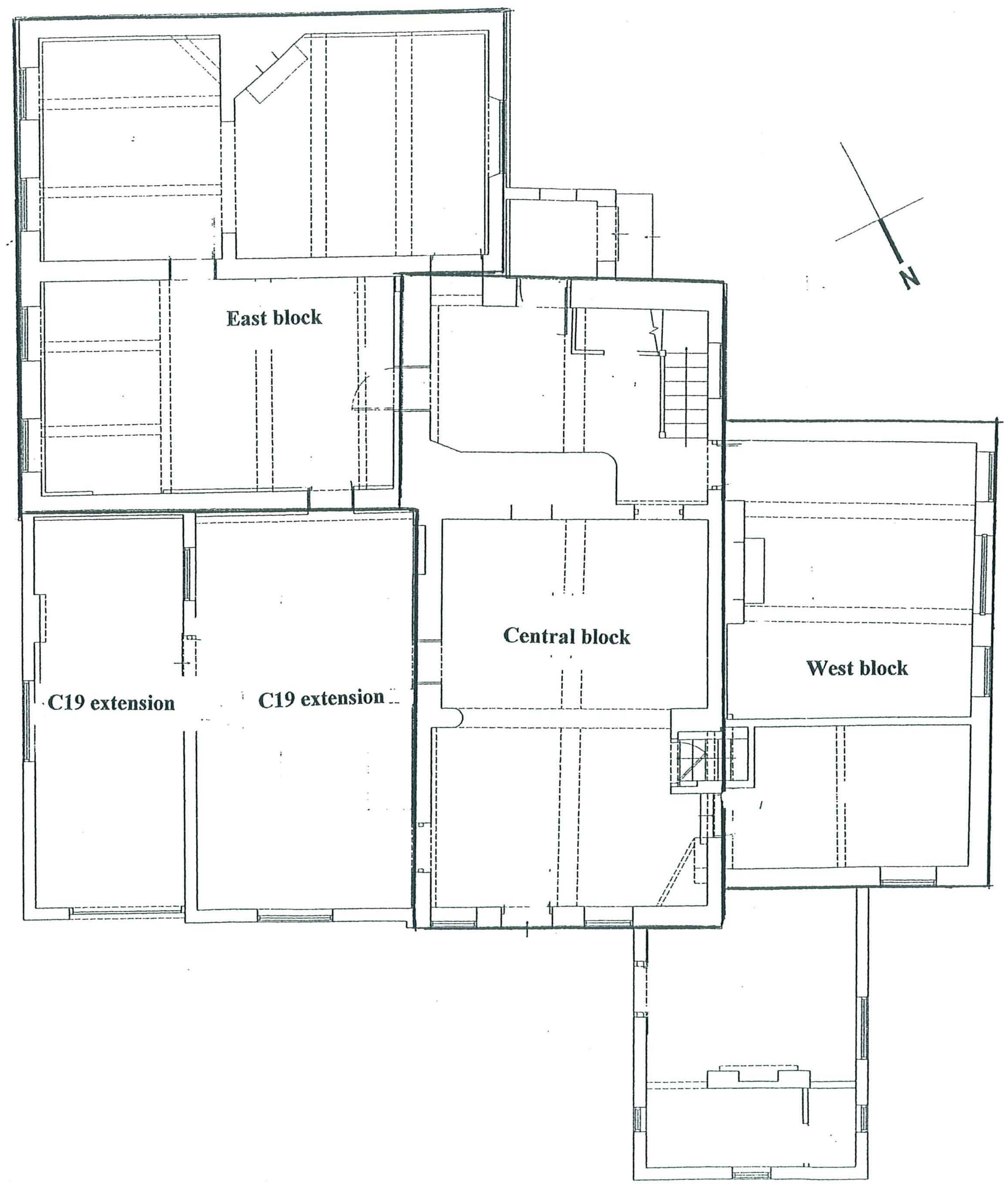


Figure 3a: Plan to show approximate location of sampled timbers based on a first-floor plan

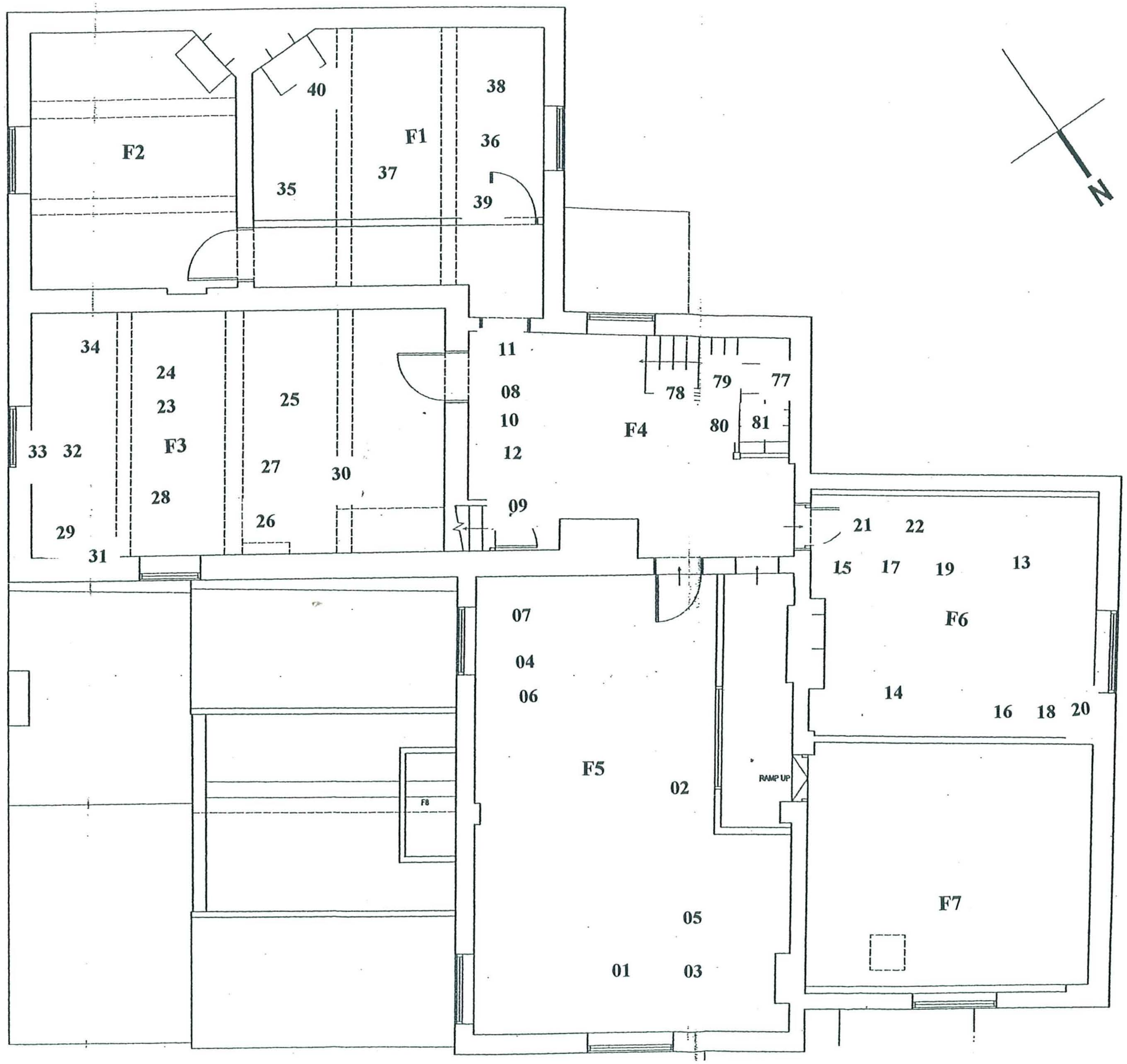


Figure 3b: Plan to show approximate location of sampled timbers based on a second-floor plan

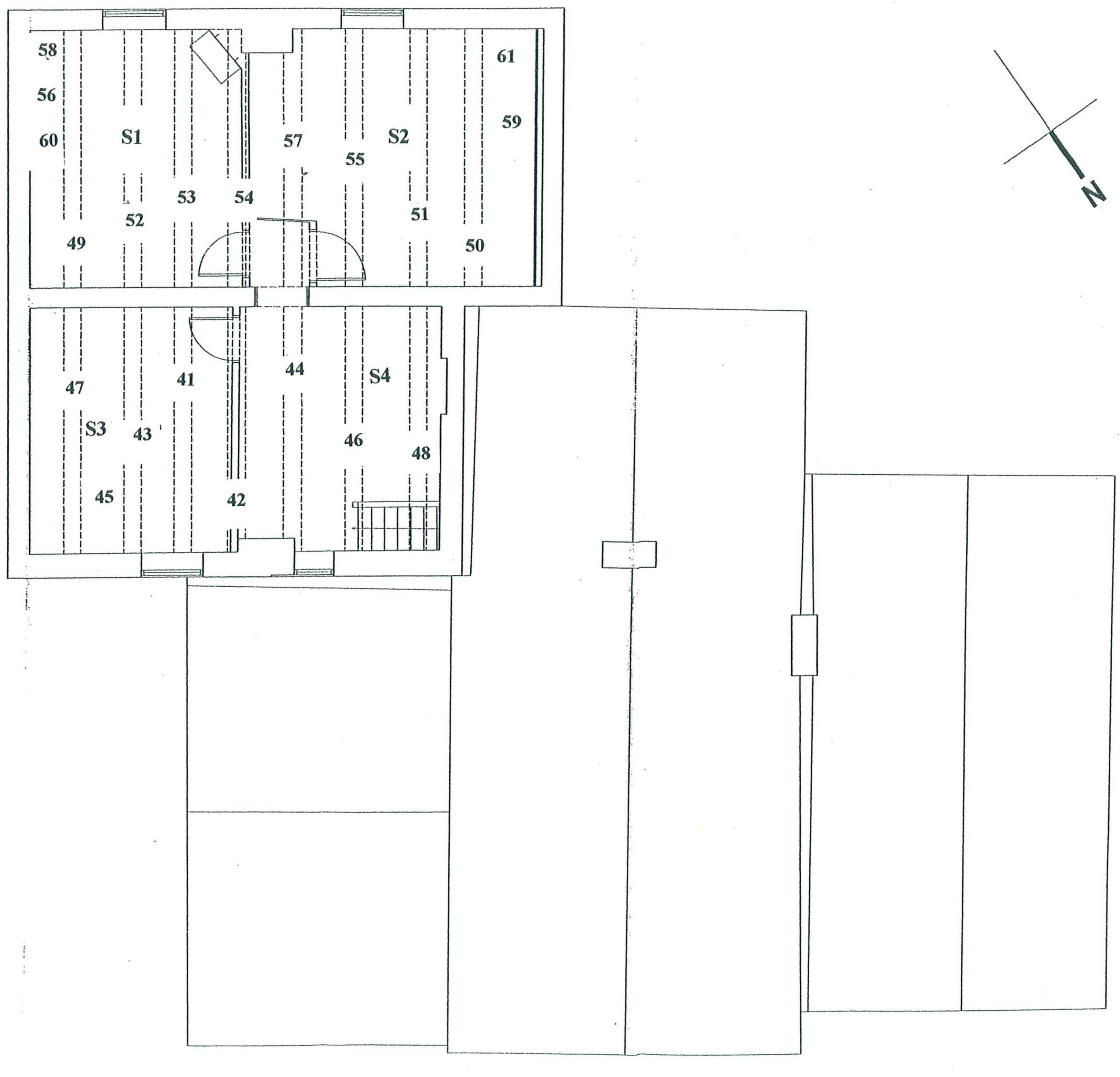


Figure 3c: Plan to show approximate location of sampled timbers based on a second-floor plan

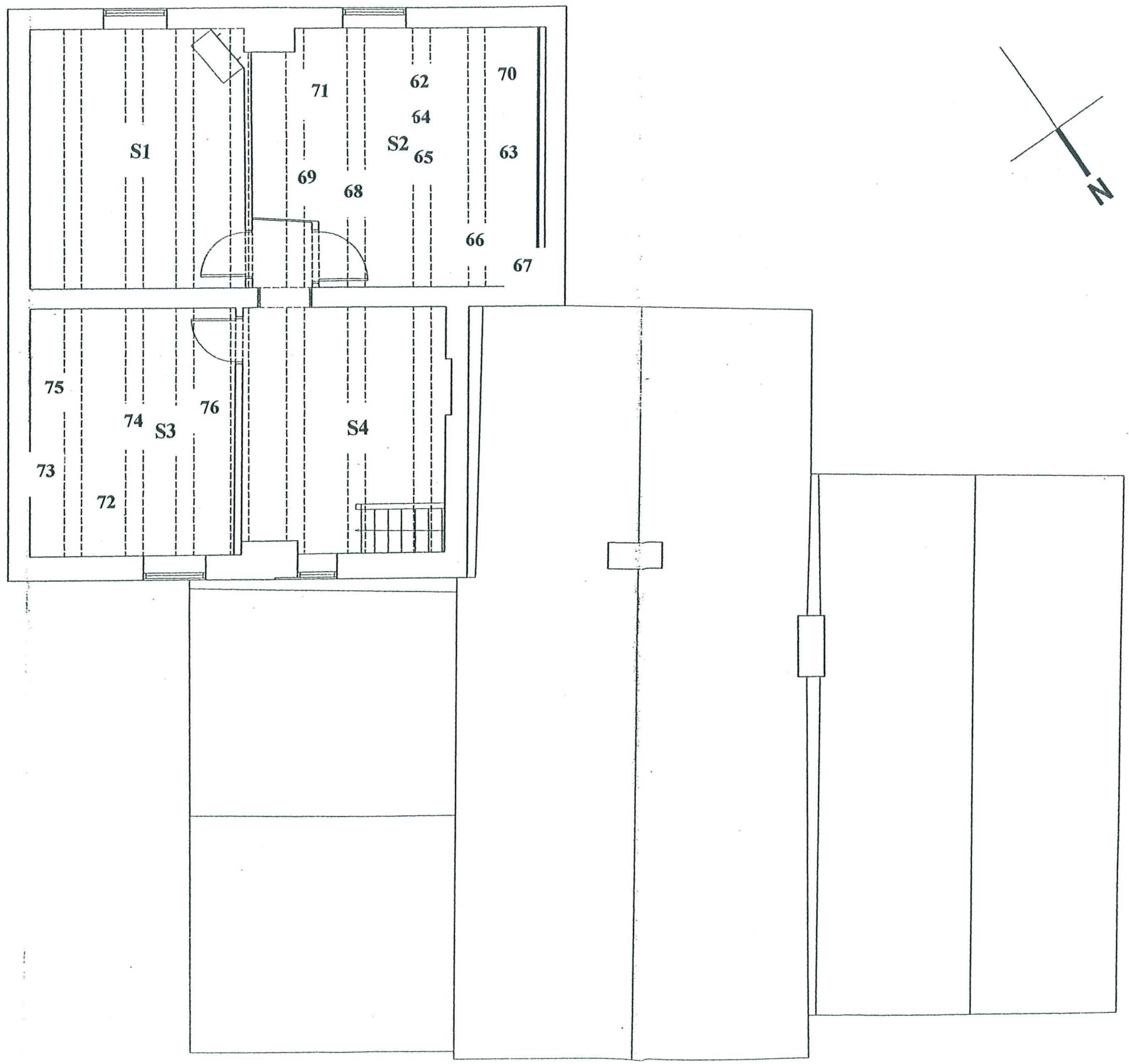
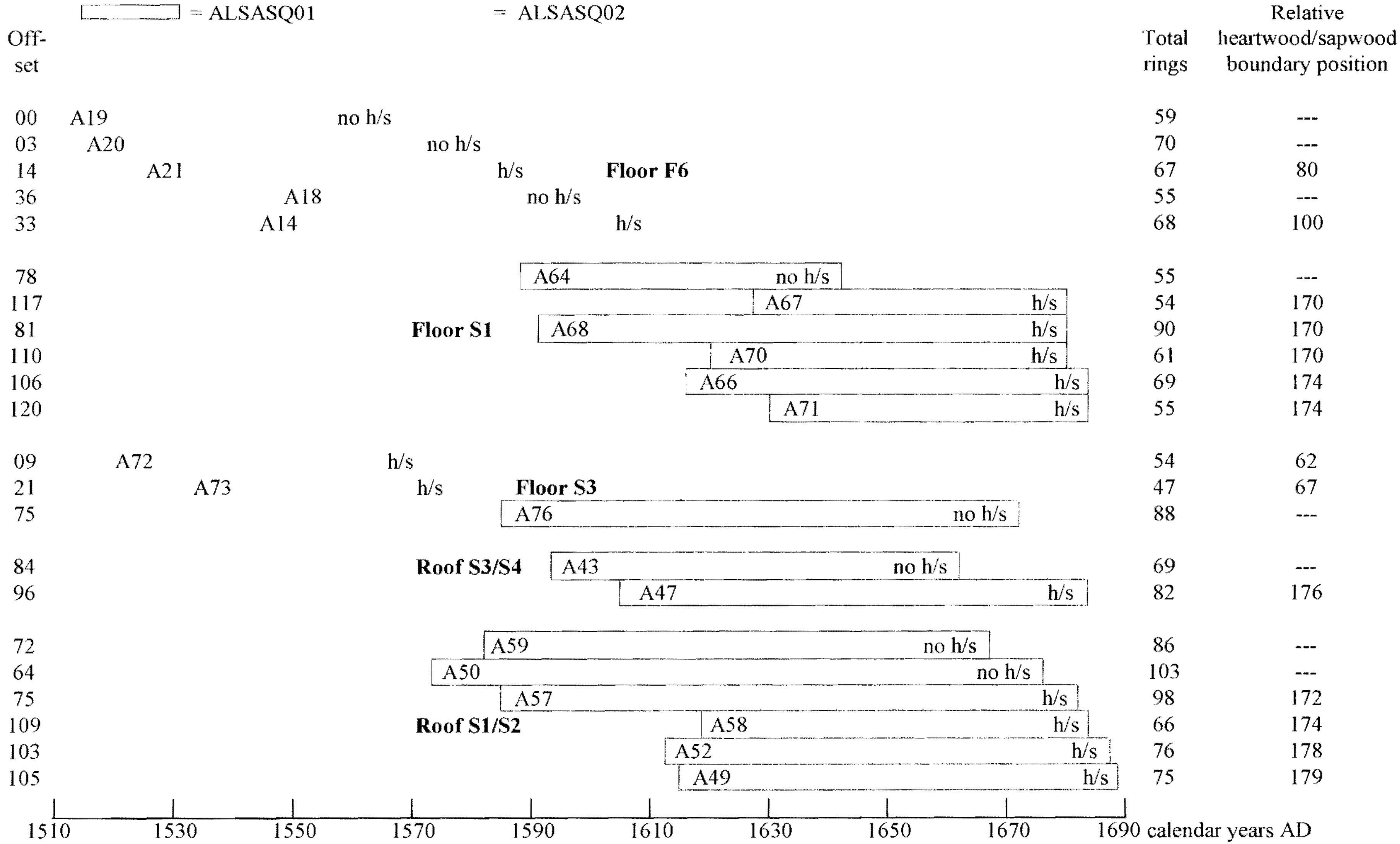


Figure 4: Bar diagram of all dated samples in site chronologies ALSASQ01 and ALSASQ02 sorted by location in relative last ring order



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

Figure 5: Bar diagrams of the samples in site chronology ALSASQ03

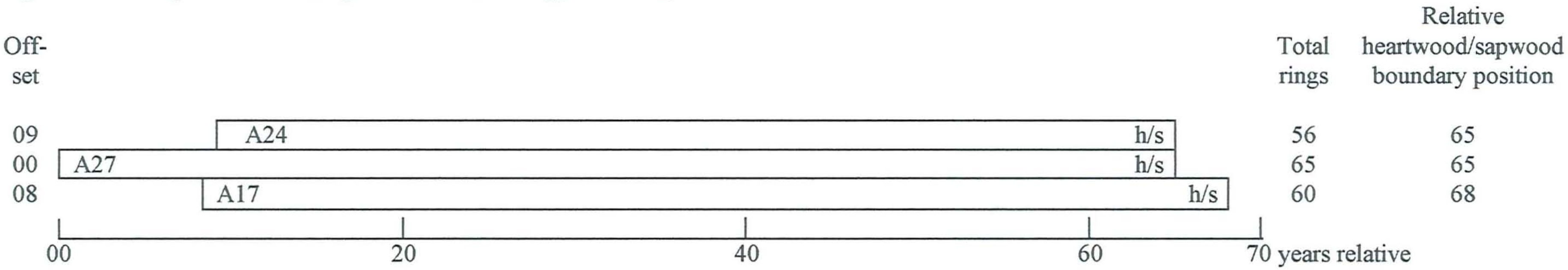
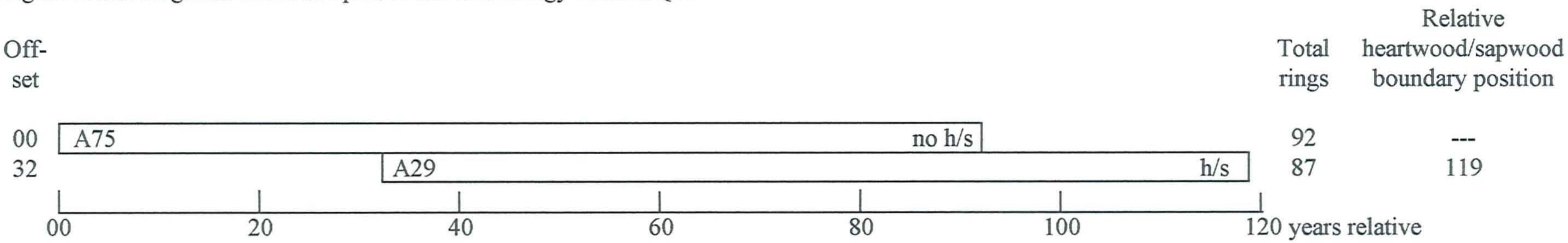


Figure 6: Bar diagrams of the samples in site chronology ALSASQ04



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

Data of measured samples – measurements in 0,01 mm units

ALS-A01A 71
324 518 466 420 300 393 562 524 507 523 317 441 488 459 409 516 458 449 380 305
341 380 359 419 322 268 156 242 301 292 294 261 182 249 218 190 227 193 293 243
226 240 216 268 251 280 202 219 183 217 207 209 181 181 166 219 206 168 166 188
249 239 251 200 230 138 131 169 149 163 185
ALS-A01B 71
373 556 423 348 301 395 555 538 509 519 320 449 492 457 407 505 482 444 386 304
336 383 366 405 323 266 170 244 298 296 290 248 183 219 210 171 223 190 276 249
227 219 258 264 227 305 184 246 197 183 220 217 176 181 162 231 199 177 168 174
227 232 246 204 206 158 128 172 152 175 146
ALS-A02A 54
253 323 295 722 371 296 540 439 456 493 517 540 358 404 414 449 354 402 506 374
347 501 635 460 463 422 550 339 627 504 375 515 615 642 605 650 632 410 412 518
440 495 437 586 284 387 384 330 348 295 360 327 331 259
ALS-A02B 54
232 310 314 341 355 320 560 433 455 481 495 534 388 360 429 475 420 392 491 396
330 481 610 460 458 439 542 344 640 501 472 464 616 583 649 641 634 373 483 506
425 468 444 561 306 354 369 316 346 251 361 320 344 265
ALS-A03A 55
459 353 255 194 182 149 164 164 225 172 171 113 118 168 171 228 216 153 171 162
119 53 58 103 125 179 196 51 93 134 172 136 170 156 162 147 178 151 195 205
128 153 155 125 56 61 111 110 174 190 159 158 155 150 191
ALS-A03B 55
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122 51 71 86 141 184 200 53 93 113 158 199 171 150 175 138 182 144 193 198
164 166 162 121 54 56 112 131 163 206 127 154 162 159 179
ALS-A04A 54
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383 399 341 432 353 400 483 518 384 358 439 545 507 569
ALS-A04B 54
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365 397 346 421 396 401 465 489 387 385 478 498 518 539
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178 70 94 100 132 139 155 137 124 147 160 56 56 89 105 136 153 86 126 163
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73 82 111 115 103 228 118 197 179
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289 206 210 214 171 237 163 261 274 329 290 269 154 236 342
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210 227 265 611 339 462 546 725 614 512 413 485 550 375 544 505 433 708 530 539
317 571 389 445 571 657 518 485 484 403 462 534 557 270 249 115 58 66 62 62
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87 79 68 80 108 125 123
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76 67 97 113 111 120 154 142 112 80 56 66 68 91
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64 122 101 86 135 182 80 101 137 105 95 126 127 181
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64 139 99 85 137 175 90 106 133 87 104 122 98 166
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90 122 200 152 190 125 142 87 154 124 120 90 114 154
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114 96 220 139 197 118 154 81 135 120 132 96 116 153
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117 140 122 118 141 115 113 122 131 172 110 109 144 180 193 82 95
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84 64 53 62 60 81 82 80 94 74 72 76 79 80 67 96 83
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198 259 278 176 212 191 234 100 138 124 272 307 271 187 198 103 140 104 124 210
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83 122 186 280 186 169 134 241 160 143 141 272 272 243 192
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73 44 84

ALS-A50B 103
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113 135 313 267 371 296 259 253 218 176 207 248 272 218 189 263 212 173 177 193
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154 129 160 129 193 200 161 192 152 94 65 87 123 170 178 196 178 216
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134 139 120 133 111 112 72 76 103 100 67 76 86 167 122 166 204 198 195 163
145 215 187 162 178 195 180 227 207 167 218 154 210 191 86 80 41 48 35 42
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138 177 168 124 159 163 135 176 153 197 168 134 159 122 113
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212 171 226 189 254 291 162 125 97 91 112 126 203 179 201 158 119 129 96 121
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196 230 189 243 208 113 88 92 113 138 238 303 295 304
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82 53 60 73 121 270 184 356 270 261 313 281 334 388 180 169 140 100 141 109
183 248 196 241 191 115 90 80 113 143 230 291 284 303
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147 218 188 148 218 134 92 114 108 124 211 242 263 230 112 69 58 65 78 172
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95 198 243 252 248 184 255 186 247
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94 184 245 236 237 220 287 179 174
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142 123 146 121 134 123 101 67 77 68 104 121 137 174
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172 200 218 171 197 134 105 80 73 111 70 88 83 96 124 145 208 187 122 86
66 67 63 120 278 291 235 207 236 227 156 165 204 191 229 240 185 175 199 190
227 188 150 96 124 161 205 154 206 155
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192 186 171 157 77 39 41 85 81 147 146 113 127 136 138 126 198 195 270 208
164 207 206 182 190 134 101 83 83 118 67 81 94 98 118 155 206 185 149 86
72 57 65 135 272 290 230 215 229 233 156 154 198 186 248 213 196 186 215 198
223 176 141 93 123 160 175 182 204 179

ALS-A69A 54
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138 221 339 313 277 272 371 241 242 134 123 137 142 142
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145 228 326 323 276 279 361 232 253 147 142 125 142 134
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178 216 98 128 125 189 145 94 90 104 58 88 83 69 86 113 127 102 137 84
69 58 63 72 87 146 143 180 142 160 136 161 152 136 93 90 103 138 154 222
245
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133 120 98 80 89 72 99 162 243 203 209 122 124 77 97
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54 63 80 140 132 116 230 207 239 255 378 426 272 364
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ALS-A75A 92
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121 95 114 142 152 150 178 185 243 290 135 161
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91 72 106 149 174 139 137 133 82 87 131 179 222 247 104 59 46 68 77 107
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112 97 128 149 148 137 167 180 238 305 135 172
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61 75 48 73 56 83 87 120
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235 241 275 333 176 163 132 183 275 165 66 119 97 240 176 356 281 238 130 136
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82 58 55 99 110 102 238 247 168 232 185 80 187 153 189 224
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83 45 42 64 142 60 116 101 132 67 113 179 255 216
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104 96 125 146 197 64 44 78 38 65 64 72 90 115 118 184 214 135 168 160
96 171
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105 95 129 145 227 60 56 78 38 53 62 72 90 102 131 174 212 138 150 136
101 172
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179 172 74 136 144 204 198 190 143 153 181 170 76 147 189

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201 244 384 71 52 36 28 45 53 66 73 53 51 51 77 95 93 105 183 223
164 159 86 160 188 223 216 200 124 160 183 177 69 139 190
ALS-A81A 84
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422 415 434 483 465 467 364 341 400 281 60 35 45 44 75 102 104 79 147 165
192 172 183 140 64 44 63 81 107 148 133 126 82 79 94 93 133 82 100 84
88 91 75 98
ALS-A81B 84
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37 53 36 24 93 125 132 159 161 171 124 88 157 277 377 329 400 384 472 501
402 428 433 482 459 473 363 341 394 285 60 35 41 33 78 106 103 74 145 168
201 163 179 142 63 42 68 86 96 145 144 116 86 78 96 90 133 82 94 83
94 75 97 94

of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

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

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

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

Bar Diagram

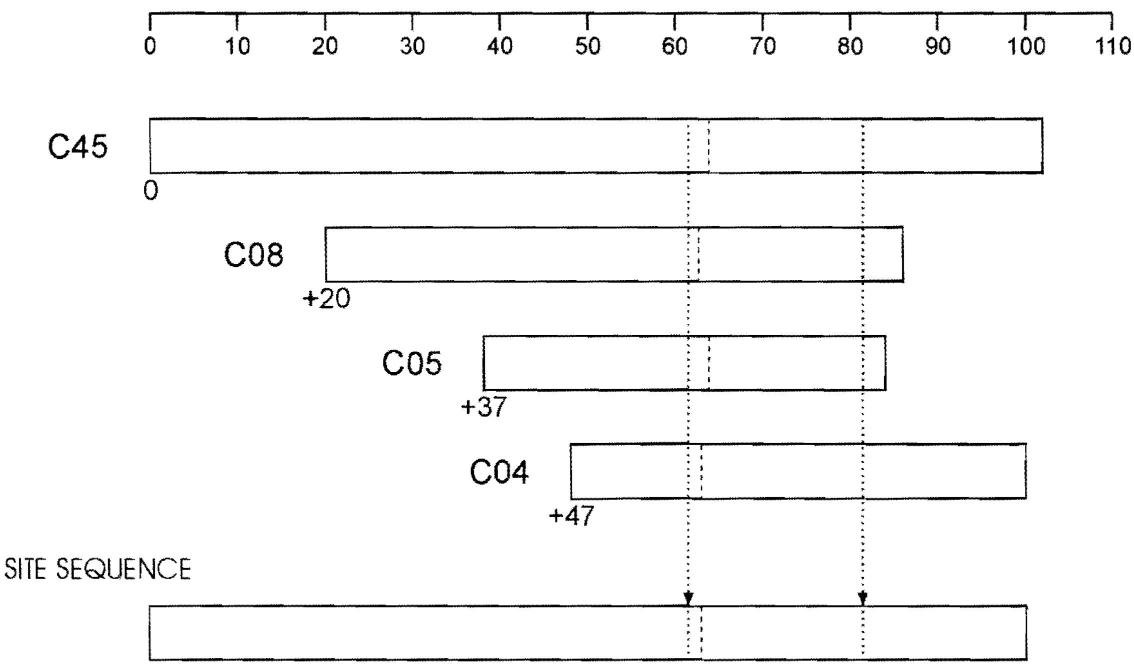


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t*-values.

The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6.

The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

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

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

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

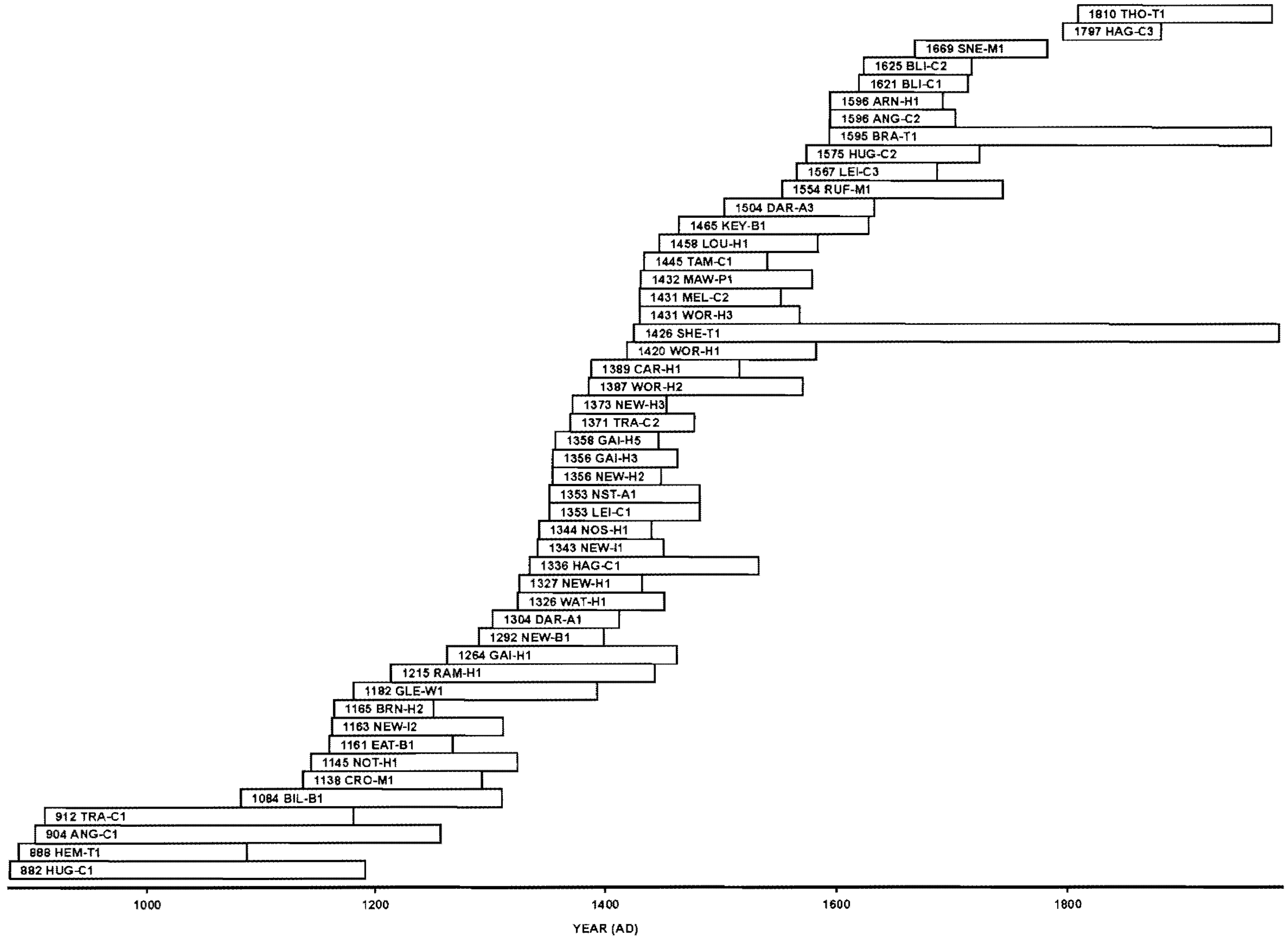
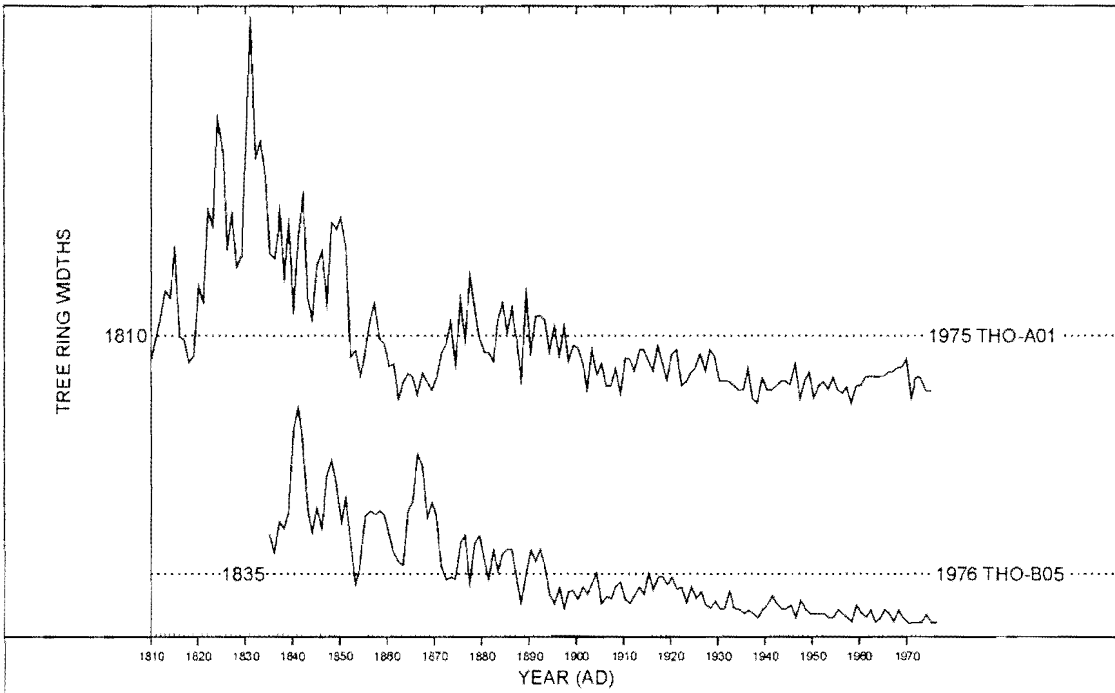


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

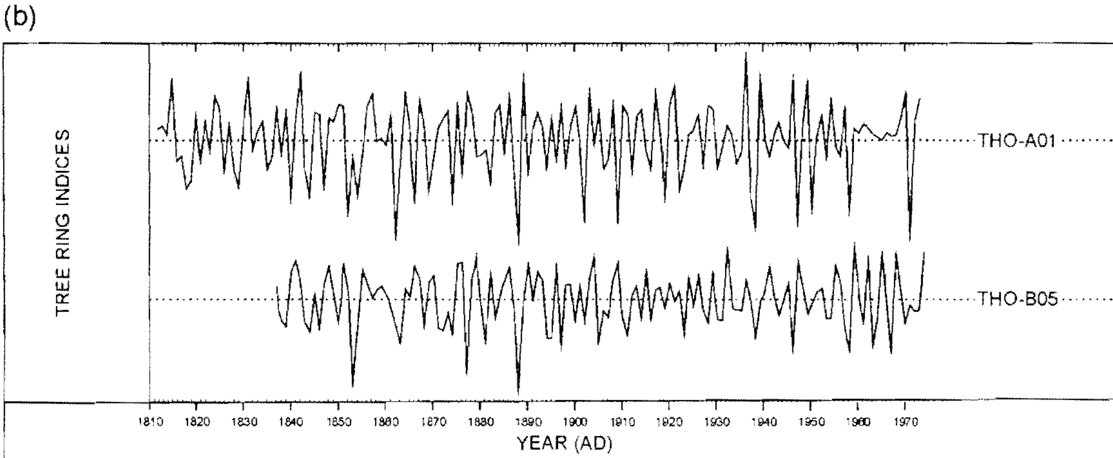


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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