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WILLIMOTESWICK, BARDON MILL, NORTHUMBERLAND
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY
Tree-ring analysis was undertaken on samples from timbers of the East range roof (north and south parts) and floor (south) and from the North range roof, resulting in the construction and dating of a single site sequence. This site sequence contains 36 samples and spans the period AD 1330–1575.
The East range (south) roof is constructed from timbers felled in AD 1491–1514 whilst the North range roof contains timbers felled in AD 1498–1523. The similarity of these felling date ranges means these two structures are broadly coeval, with the possibility that the North range slightly post-dates the East range (south) roof. The floor frame of the East range (south) is now thought to have been constructed in AD 1575, utilising reused timber of the late-fifteenth/early sixteenth century, possibly from the original building, for some of the smaller, common joists. The latest roof is that of the East range (north) where timber has been dated to AD 1575. The dendrochronology has demonstrated that construction of all three parts under investigation, and thus by association the gatehouse, was undertaken over a period of less than 100 years.

CONTRIBUTORS
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ACKNOWLEDGEMENTS
The Laboratory would like to thank Mr and Mrs Storrow, the owners of the buildings, for allowing sampling to be undertaken and for their assistance and understanding during the procedure. We would also like to thank Martin Roberts, Historic Buildings Inspector at English Heritage's Newcastle office, for his invaluable on-site advice and for providing Figures 11–28, upon which the location of samples has been marked. He also provided much of the description of the two ranges used in the introduction below. Thanks are also given to Cathy Tyers of the University of Sheffield Dendrochronology Laboratory and all at English Heritage's Scientific Dating Section for their assistance throughout the production of this report

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INTRODUCTION

Willimoteswick is located close to the village of Bardon Mill in Tynedale, Northumberland (Figs 1–3; NY 7707 6364). The building is grade I listed and is on the Heritage at Risk register. Additionally, the East range is a Scheduled Ancient Monument. It was the fortified manor of the Ridley family and the birthplace of Bishop Ridley, who was burned at the stake in AD 1555. Little is known as to the origins of the building but documentary evidence clearly indicates its existence by AD 1541 (Graham 1976).

The present farmhouse occupies the site of what appears to have been a double-ended hall with narrow towers at each end of the cross-wings; the east wing and its towers survive, the remainder having been rebuilt *c* AD 1900 in Tudor style. To the north-east is the well-preserved gatehouse with tunnel-vaulted carriageway and corbelled parapet (Fig 4). Adjoining this are the two-storey East range (of two parts) and the single-storey North range (Figs 5 and 6; Grundy *et al* 1976).

It has been suggested that both parts of the East range and the North range, including the gatehouse, were probably built in the century and a half between *c* AD 1500 and AD 1650 (*pers comm* Martin Roberts).

East range (south)

This part of the East range is thought to be earlier than the northern part, based on evidence from the masonry. The roof here consists of four principal-rafter with chamfered tiebeam and collar trusses (Fig 7). The floor frame in this part of the building was thought to potentially be original. It contains several large, main beams which run east-west, into which are jointed a series of smaller, secondary joists (Fig 8).

East range (north)

The northern part of the East range abuts the southern part and appears to be integral with the gatehouse. The roof consists of six substantial principal-rafter with tiebeam and collar trusses, these supporting purlins and common rafters (Fig 9). The roof timbers are larger here than in the southern part of the East range and the construction appears to be of a superior standard. It has been suggested that the gatehouse, and hence the northern part of the East range, dates to the late-sixteenth or early seventeenth century, coinciding with a period of bastle building.

North range

This range runs from the west wall of the gatehouse. Although the wall junction in the north-east corner against the gatehouse suggests it may be contemporary with the gatehouse, the quality of roof construction is much poorer than that in the impressive East range (north).

Its roof is of five tiebeam and principal-rafter trusses (Fig 10). They rest on a north wall that is clearly earlier than the range at its eastern and western ends. Its southern wall is a much later arched hemmel wall of probably nineteenth-century date. The trusses are numbered from the east though the tiebeam of truss 1 has clearly been renewed in recent times. The construction is clearly ancient, and looks like the East range (south) in the size of its timbers, but compared to that roof, it seems less efficiently built.

SAMPLING

Sampling was requested by Martin Roberts at English Heritage's North-East Regional Office to inform grant-aided repairs and to obtain a better understanding of the chronological development of the building. Although the gatehouse itself does not contain any timber which would allow tree-ring dating to be undertaken, it is thought that the northern section of the East range is integral to it and, therefore, dating this should provide dating evidence for the gatehouse.

In accordance with the brief provided by English Heritage and the Class VI Scheduled Monument Consent attached to this site, a total of 40 timbers was sampled. Each sample was given the code WLM-W (for Willimoteswick) and numbered 01–40. The location of samples was noted at the time of sampling and has been marked on Figures 11–28. Further details relating to the samples can be found in Table 1. Trusses and bays were numbered from north to south (East range) and from east to west (North range). Although the potentially original floor continued along the length of the East range (south), it was not possible to access all parts of the ground floor due to the presence of unwell lambs and, therefore, sampling of these beams was restricted to two ceiling bays only (Fig 12).

ANALYSIS AND RESULTS

At this stage it was noticed that one of the samples from the North range roof (WLM-W35) had too few rings to make secure dating a possibility and so it was rejected prior to measurement. The remaining 39 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a minimum value of t=4.5, 36 samples matched each other.

The data of these 36 samples were combined at the relevant offset positions to form WLMWSQ01, a site sequence of 246 rings (Fig 29). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1330 and a last-measured ring date of AD 1575. The evidence for this dating is given in Table 2.

Attempts to date the remaining ungrouped three samples by individually comparing them against the reference chronologies were unsuccessful and these remain undated.

INTERPRETATION

Analysis of samples taken from timbers at this site has resulted in the construction and dating of a single site sequence. Site sequence WLMWSQ01 contains 36 samples, from all areas under investigation, and spans the period AD 1330–1575. For the purpose of clarity, each group of timbers have been dealt with separately according to area and structure (Fig 30).

East range (south)

Roof

Seven of the samples taken from this roof have been successfully dated. Five of these have the heartwood/sapwood boundary ring date, which in all cases is similar and suggestive of a single felling. The average heartwood/sapwood boundary ring is AD 1474, allowing an estimated felling date to be calculated for the five timbers represented to within the range AD 1491–1514. This allows for sample WLM-W14 to have a last-measured ring of AD 1490 with incomplete sapwood. The last two roof samples do not have the heartwood/sapwood boundary ring and, therefore, an estimated felling date cannot be calculated for them, except to say that this would be estimated to be after AD 1459 (WLM-W13) and after AD 1462 (WLM-W19) at the earliest, *termini post quem* which do not preclude these samples from also having been felled in AD 1491–1514.

Floor

Eight of the samples taken from the timbers of the floor structure in this part of the building have also been dated. This dating clearly demonstrates that two separate fellings are represented within the timbers, with the joists being earlier than the main beams.

Sample WLM-W26, taken from a joist, has complete sapwood and the last-measured ring date of AD 1496, the felling date of the timber represented. Four further joists have the heartwood/sapwood boundary ring; in the case of three of these, this is broadly contemporary and suggestive of a single felling. The average of these heartwood/sapwood boundary ring dates is AD 1471, allowing an estimated felling date to be calculated for the three timbers represented to within the range AD 1486–1511, consistent with a felling of AD 1496. The fourth sample has the earlier heartwood/sapwood boundary ring date of AD 1456, calculating to an estimated felling date range of AD 1471–96, again just consistent with a felling of AD 1496. Support for the contemporary felling of WLM-W28 with the rest of the joists is given by the overall level of crossmatching seen between this sample and the other joists. Therefore, although the timber represented might feasibly be felled earlier it seems more likely that it simply has a relatively large number of sapwood rings.

Three of the samples taking from the main beams also have complete sapwood. Two of these, (WLM-W22 and WLM-W23) have the last-measured ring date of AD 1574. When these two samples are looked at under the microscope the spring growth cells, but no summer growth cells, of the following year can be seen, demonstrating that the two timbers represented were felled in summer AD 1575. The fourth sample with complete sapwood, WLM-W21, has the last-measured ring date of AD 1575 and was felled in winter AD 1575. Thus, it can be seen that felling of the timbers utilised may have occurred over a period of several months.

East range (north)

Eleven of the samples from the roof here have been dated. Three of these have complete sapwood and the last-measured ring date of AD 1574. When these three samples are looked at under the microscope the spring growth cells, but no summer growth cells, of the following year can be seen. This means that the three timbers represented were felled in the summer of AD 1575. A further five of the dated samples from this roof have the heartwood/sapwood boundary. In the case of four of these, this is broadly contemporary and, therefore, suggestive of a single felling. The average heartwood/sapwood boundary ring of these four samples is AD 1540, allowing an estimated felling date to be calculated for the four timbers represented to within the range AD 1555–80, consistent with these timbers also having been felled in AD 1575. Sample WLM-W01 has the slightly earlier heartwood/sapwood boundary ring date of AD 1527, which allows an estimated felling date range to be calculated for the timber of AD 1542–67. In the same way as for WLM-W28 above, it is possible that WLM-W01 is a slightly earlier timber or more likely that it is one of the 5% of mature oak trees with sapwood numbers outside the average. The final three dated samples from this roof do not have the heartwood/sapwood boundary, but all have last measured heartwood ring dates which do not preclude them from having been felled in AD 1542–67 or AD 1575.

North range

Ten of the samples from this part of the building have been successfully dated. Eight of these have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date for these eight samples is AD 1483, which allows an estimated felling date to be calculated for the eight timbers represented to within the range AD 1498–1523. The two samples without the heartwood/sapwood boundary both have last heartwood ring dates in the mid-fifteenth century, which makes it possible that they were also felled in AD 1498–1523.

All felling date ranges have been calculated using the estimate that 95% of mature oak trees in this region have between 15 and 40 sapwood rings.

Discussion

Prior to the tree-ring dating being undertaken it was thought that the earliest, surviving timbers would be in the East range (south). Structural analysis had suggested that the East range (north) was likely to be contemporary with the gatehouse. There had been the suggestion that the North range might also be of the same date as the gatehouse. However, with the roof here being stylistically quite similar to that of the East range (south), this was more uncertain.

As expected, the earliest timbers have been found in the East range (south), but also in the North range. The roof of the East range (south) is now known to have been constructed from timbers felled in AD 1491–1514, whilst the North range contains timber which was felled in AD 1498–1523. These felling date ranges are very similar and suggest that these ranges are at least broadly coeval. It had already been noted that these two roofs were similar in appearance and so perhaps this is unsurprising. It is possible that construction of the East range (south) slightly predates that of the North range, as it can be seen that the heartwood/sapwood boundary ring dates of the former's timbers are generally earlier than those of the latter. However, this may simply be due to the timbers of the North range roof have fewer sapwood rings than those of the East range (south) roof.

At least one of the common joists of the floor frame within the East range (south) has been dated to AD 1496, with several others having felling date ranges also consistent with this felling. Other, larger, main joists from this floor structure have been dated to AD 1575. It seems likely that this floor structure dates to AD 1575 but, despite no evidence for reuse or resetting noted at the time of sampling, also incorporates reused timber of the late-fifteenth century. It is perhaps understandable that trees would be cut for the large, main beams, whereas reused timbers could be cut down to form common joists. The similarity in dates gained for the common joists and the roof timbers of this range makes it possible that these timbers were cut as part of the same felling activity. It should be noted that, due to issues with access, this dating only relates to two ceiling bays, although there is no reason to think the rest of the floor structure would produce different results.

The latest roof is that of the East range (north). Here timber has been dated to AD 1575, with construction thought likely to have occurred shortly after. It appears that at the same time this roof was being erected, modifications were being undertaken to the southern part of this building involving the insertion of a new/replacement floor frame. By association it is now possible to give the gatehouse a likely construction date of AD 1575, and also to dismiss the suggestion that the North range is contemporary with it.

Construction of the three parts under investigation and the gatehouse is likely to have occurred over a period of about 80 years, rather than the 150 years previously postulated.

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Table 1: Details of tree-ring samples from Willimoteswick, Bardon Mill, Northumberland

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
East range (north) roof						
WLM-W01	East principal rafter, truss 1	116	h/s	1412	1527	1527
WLM-W02	Tiebeam, truss 1	84	h/s	----	----	----
WLM-W03	East principal rafter, truss 3	116	--	1361	----	1476
WLM-W04	Tiebeam, truss 3	70	29C	1505	1545	1574
WLM-W05	Tiebeam, truss 4	189	01	1358	1545	1546
WLM-W06	Collar, truss 4	139	09	1410	1539	1548
WLM-W07	West principal rafter, truss 5	93	03	1449	1538	1541
WLM-W08	Tiebeam, truss 5	117	--	1379	----	1495
WLM-W09	West principal rafter, truss 6	145	25C	1430	1549	1574
WLM-W10	Collar, truss 6	152	h/s	1386	1537	1537
WLM-W11	Tiebeam, truss 2	114	--	1429	----	1542
WLM-W12	West lower purlin, truss 1-2	69	29C	1506	1545	1574
East range (south) roof						
WLM-W13	West principal rafter, truss 9	80	--	1365	----	1444
WLM-W14	Tiebeam, truss 9	107	14	1384	1476	1490
WLM-W15	West principal rafter, truss 7	135	h/s	1336	1470	1470
WLM-W16	Tiebeam, truss 7	113	h/s	1366	1478	1478
WLM-W17	West principal rafter, truss 8	134	h/s	1338	1471	1471
WLM-W18	Tiebeam, truss 8	92	h/s	1382	1473	1473
WLM-W19	West principal rafter, truss 10	96	--	1352	----	1447
WLM-W20	Tiebeam, truss 10	80	11C	----	----	----
East range (south) floor						
WLM-W21	Main beam 3	131	29C	1445	1546	1575
WLM-W22	Main beam 4	123	22C	1452	1552	1574
WLM-W23	Main beam 5	84	32C	1491	1542	1574

WLM-W24	Joist 4, beam 3-4	81	h/s	1390	1470	1470
WLM-W25	Joist 13, beam 3-4	106	h/s	1368	1473	1473
WLM-W26	Joist 15, beam 3-4	83	20C	1414	1476	1496
WLM-W27	Joist 8, beam 4-5	121	h/s	1349	1469	1469
WLM-W28	Joist 12, beam 4-5	53	h/s	1404	1456	1456
North range; roof						
WLM-W29	Collar, truss 1	107	h/s	1378	1484	1484
WLM-W30	Tiebeam, truss 2	118	--	----	----	----
WLM-W31	North principal rafter, truss 2	58	h/s	1433	1490	1490
WLM-W32	Collar, truss 2	133	h/s	1346	1478	1478
WLM-W33	Collar, truss 3	122	--	1331	----	1452
WLM-W34	Tiebeam, truss 4	163	h/s	1330	1492	1492
WLM-W35	North principal rafter, truss 4	NM	--	----	----	----
WLM-W36	Tiebeam, truss 5	125	h/s	1350	1474	1474
WLM-W37	South principal rafter, truss 5	116	h/s	1363	1478	1478
WLM-W38	Collar, truss 5	82	h/s	1405	1486	1486
WLM-W39	South upper purlin, truss 1-2	143	h/s	1343	1485	1485
WLM-W40	North lower purlin, truss 2-3	109	--	1360	----	1468

*NM = not measured
**h/s = the heartwood/sapwood boundary ring is the last measured ring on the sample
C = complete sapwood retained on core.

Table 2: Results of the cross-matching of site sequence WLMWSQ01 and relevant reference chronologies when the first-ring date is AD 1330 and the last-ring date is AD 1575

Reference chronology	*t*-value	Span of chronology	Reference
Moot Hall, Hexham	11.6	AD 1341–1539	Arnold *et al* 2004
Tunstall Hall Farm, Hartlepool	9.1	AD 1316–1484	Howard *et al* 2002
Low Harperley Farmhouse, Wolsingham, County Durham	8.9	AD 1356–1604	Arnold *et al* 2006
Unthank Hall, Stanhope, Co Durham	8.5	AD 1386–1592	Howard *et al* 2001
Aydon Castle (latrine block), Aydon, Northumberland	8.4	AD 1406–1545	Arnold *et al* 2002
35 The Close, Newcastle upon Tyne	7.9	AD 1365–1513	Howard *et al* 1991
1–2 The College, Cathedral Precinct, Durham	7.7	AD 1364–1531	Howard *et al* 1992

Figure 1: Map to show the general location of Willimoteswick

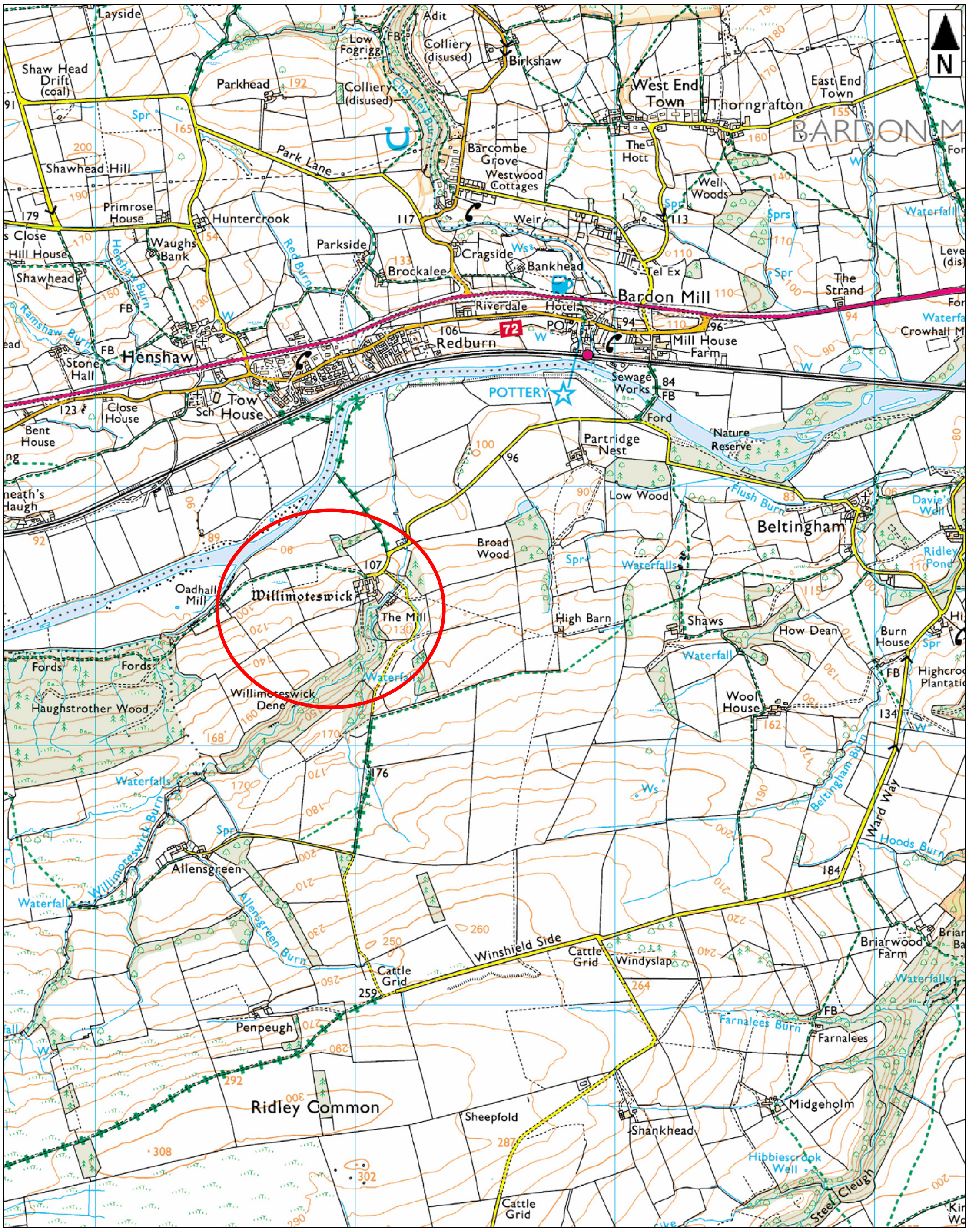

Figure 2: Map to show the location of Willimoteswick

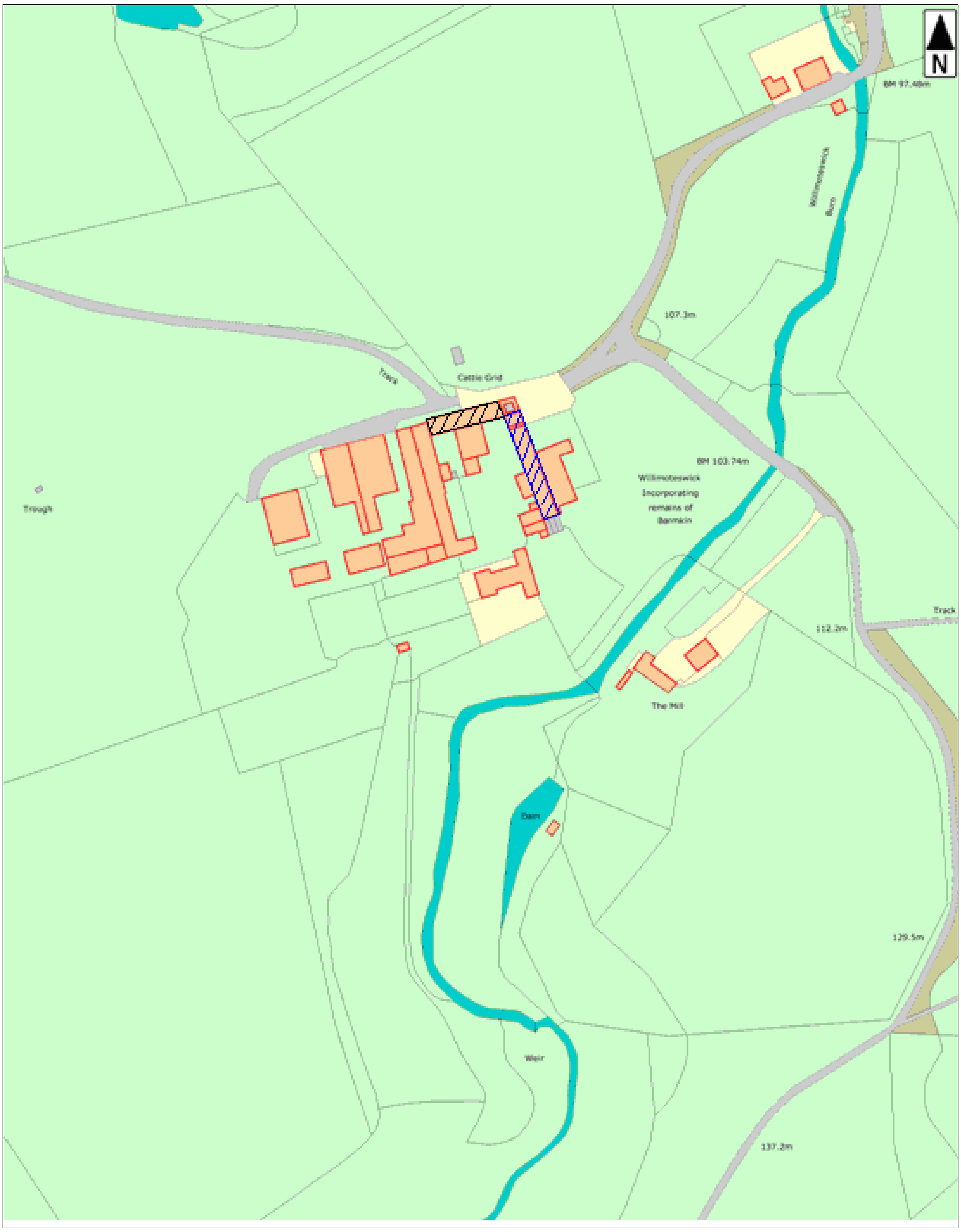

Figure 3: Site map showing Willimoteswick; North range hashed in black and East range hashed in blue

Figure 4: The gatehouse; taken from the south-west

Figure 5: East range; taken from the north-west

Figure 6: North range; taken from the south-east

Figure 7: East range (south); truss 10

Figure 8: East range (south); ground-floor ceiling

Figure 9: East range (north); truss 3 in foreground

Figure 10: North range; truss 4

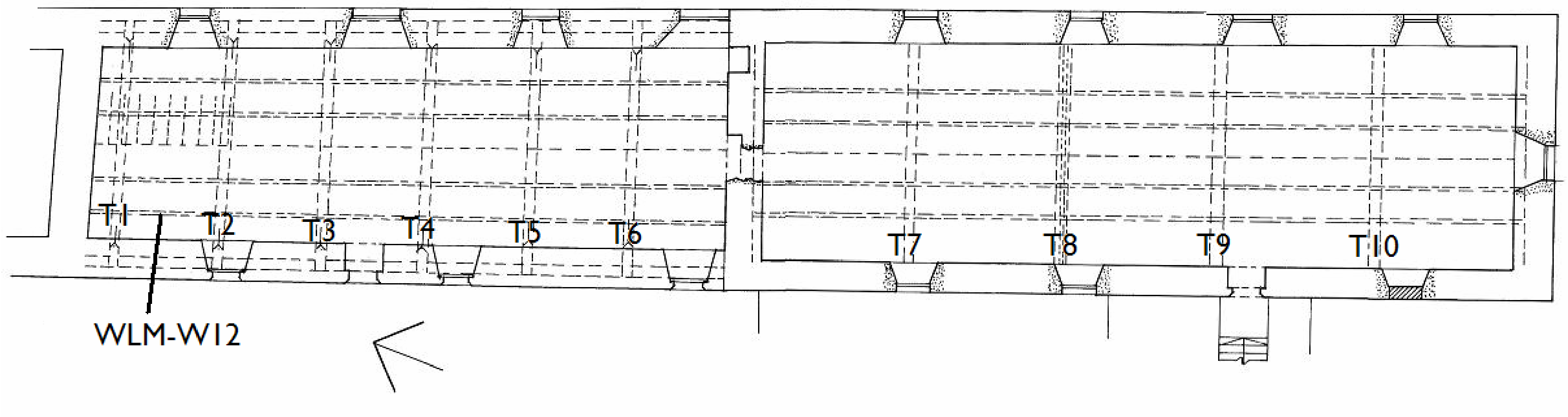

Figure 11: East range; roof plan, showing truss numbering and the location of sample WLM-W12

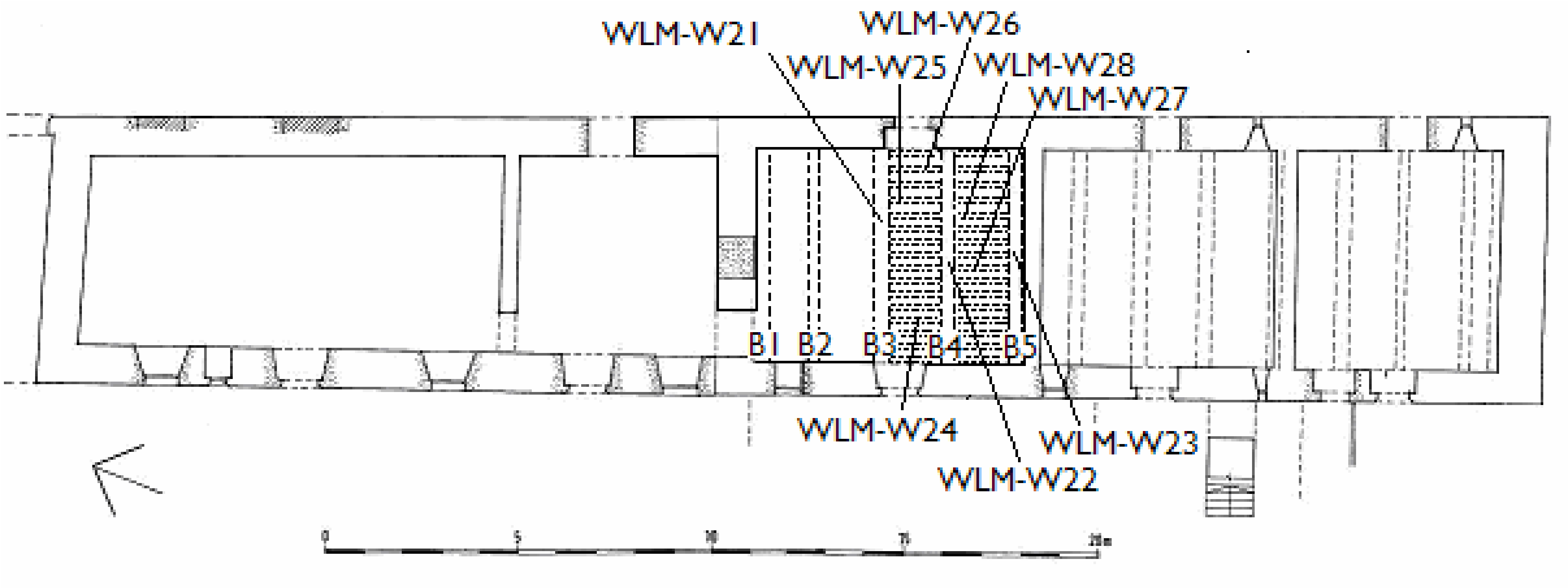

Figure 12: East range; ground-floor ceiling plan, showing the location of samples WLM-W21–8

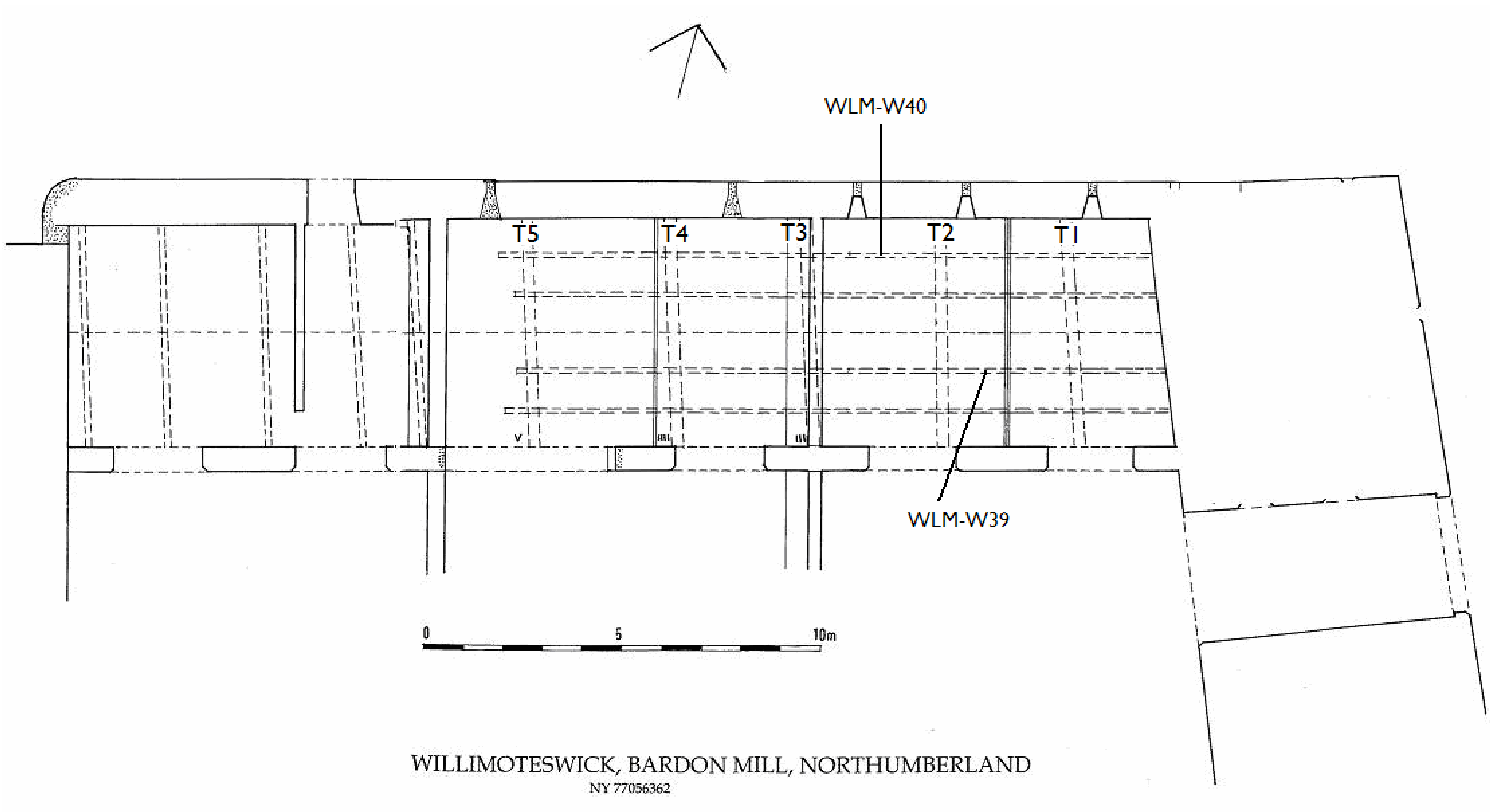

Figure 13: North range roof plan, showing the location of samples WLM-W39 and WLM-W40

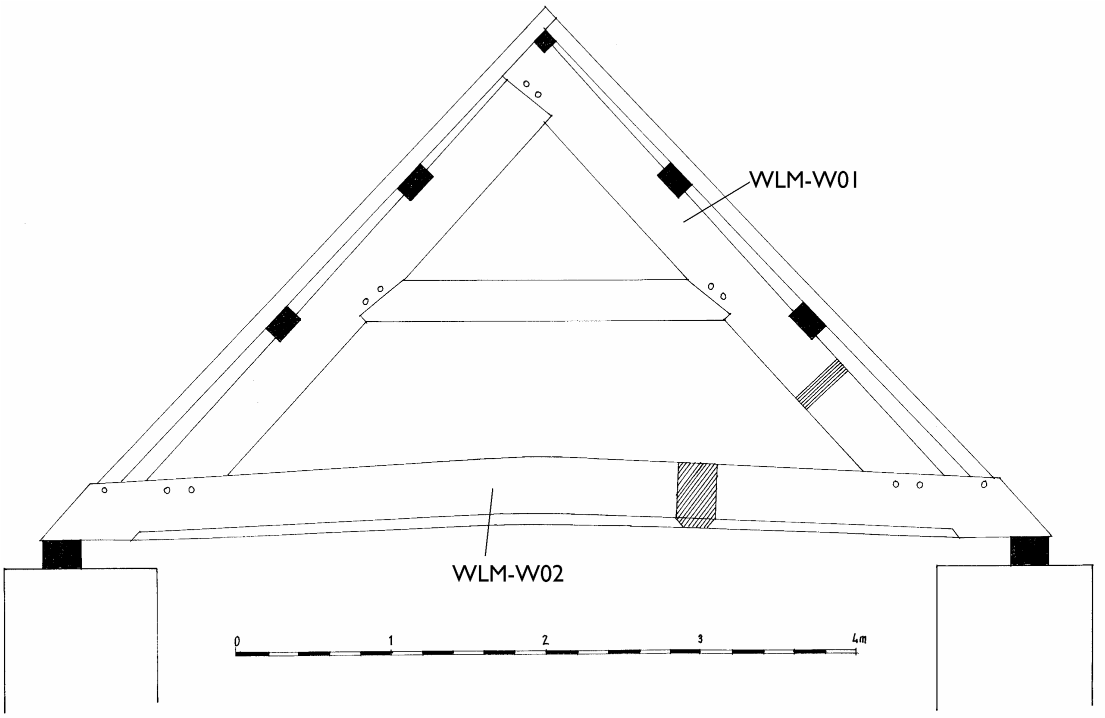

Figure 14: East range (north), truss 1 (south face), showing the location of samples WLM-W01 and WLM-W02

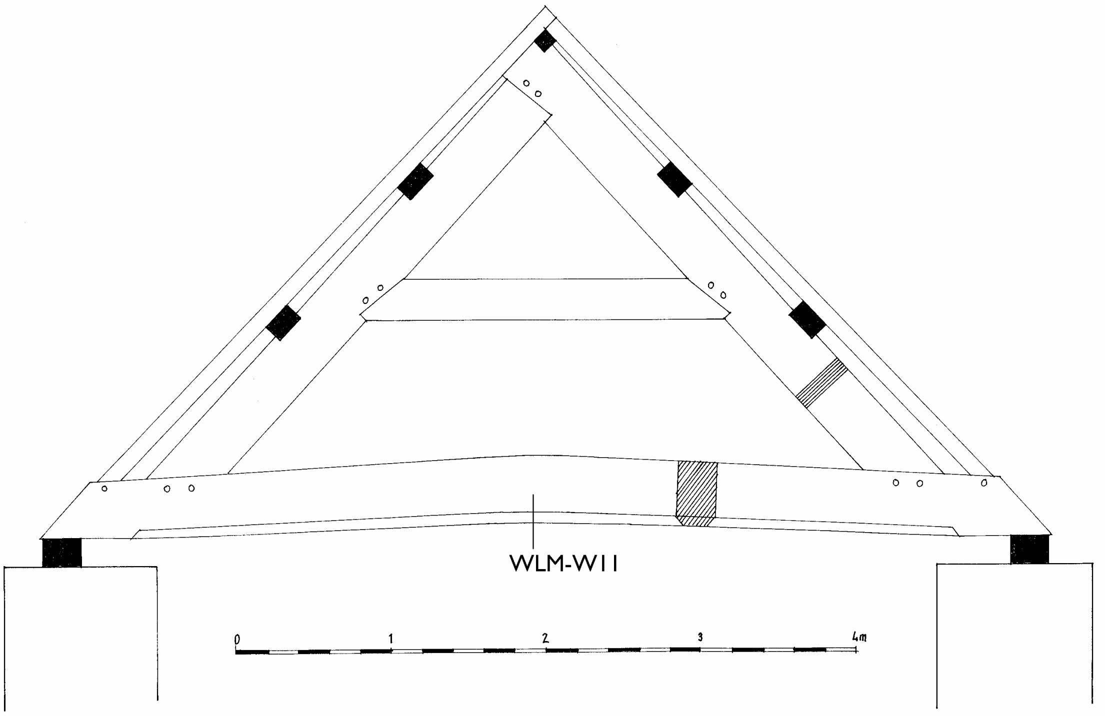

Figure 15: East range (north), truss 2 (south face), showing the location of sample WLM-W11

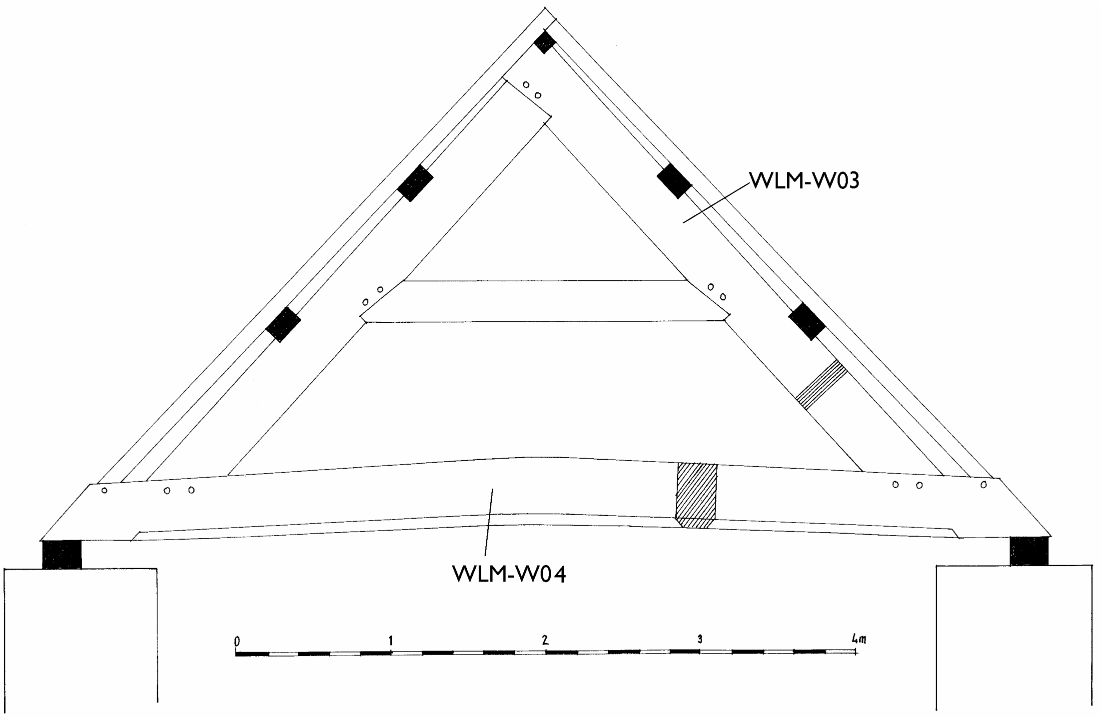

Figure 16: East range (north), truss 3 (south face), showing the location of samples WLM-W03 and WLM-W04

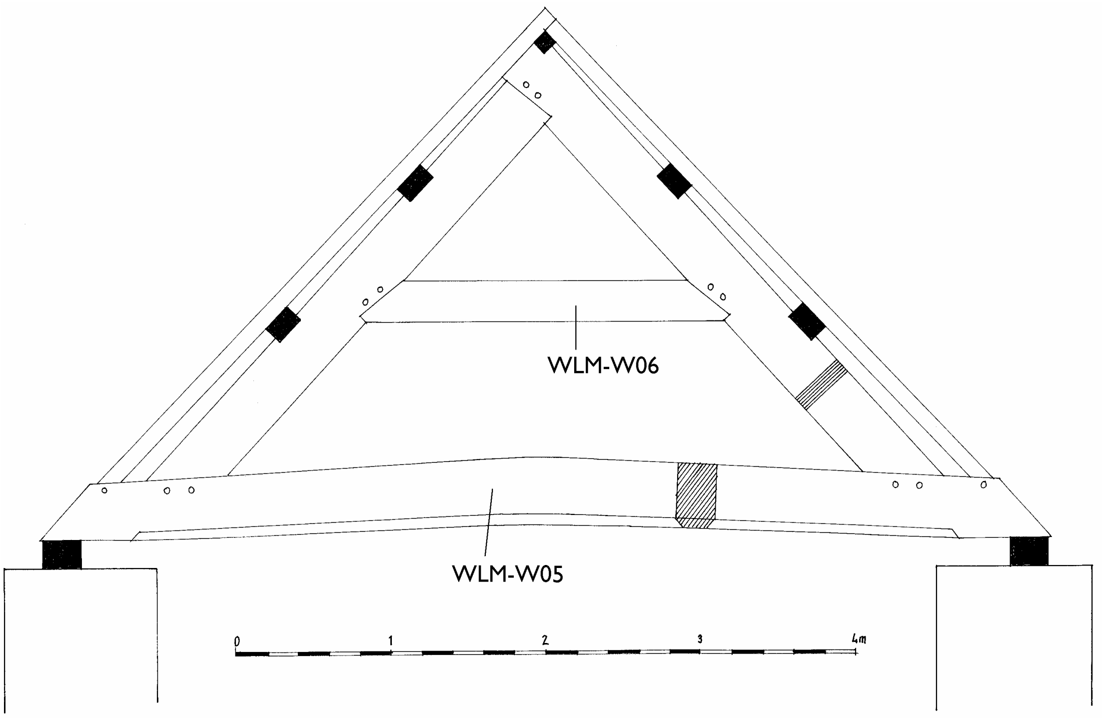

Figure 17: East range (north), truss 4 (south face), showing the location of samples WLM-W05 and WLM-W06

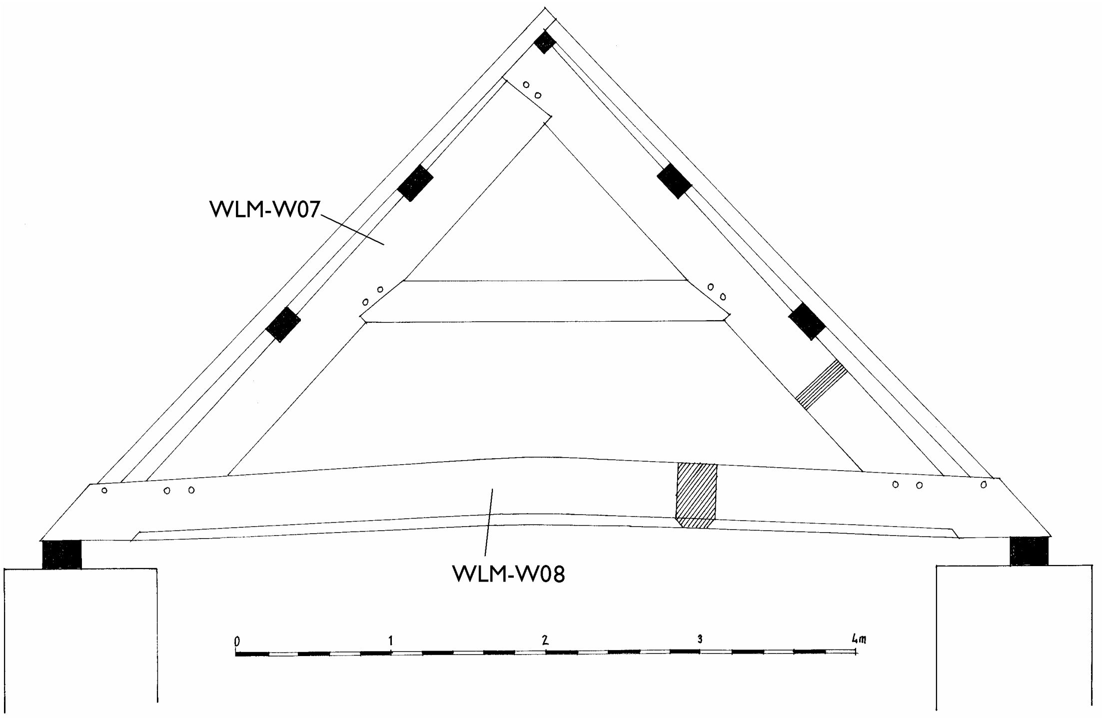

Figure 18: East range (north), truss 5 (south face), showing the location of samples WLM-W07 and WLM-W08

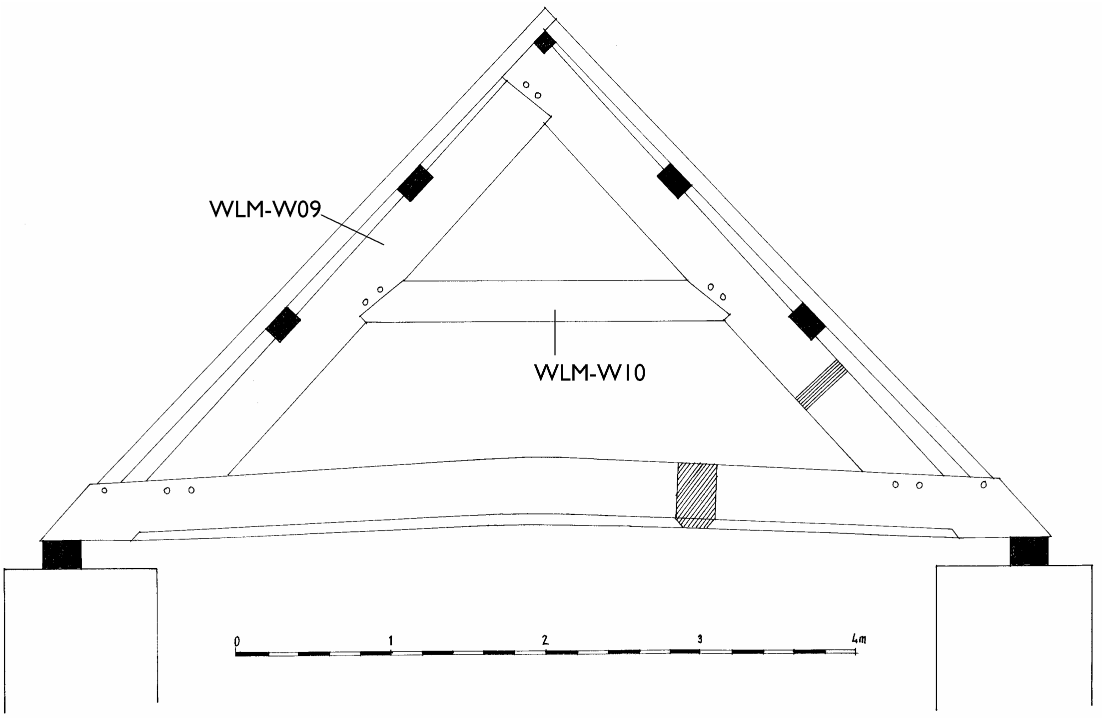

Figure 19: East range (north), truss 6 (south face), showing the location of samples WLM-W09 and WLM-W10

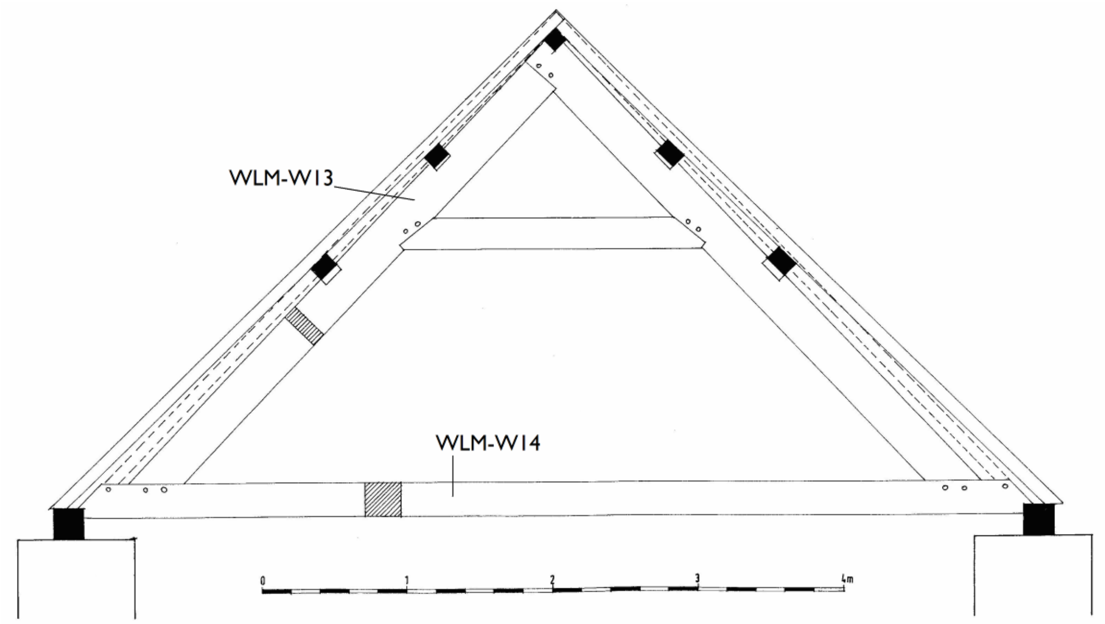

Figure 20: East range (south), truss 9 (south face), showing the location of samples WLM-W13 and WLM-W14

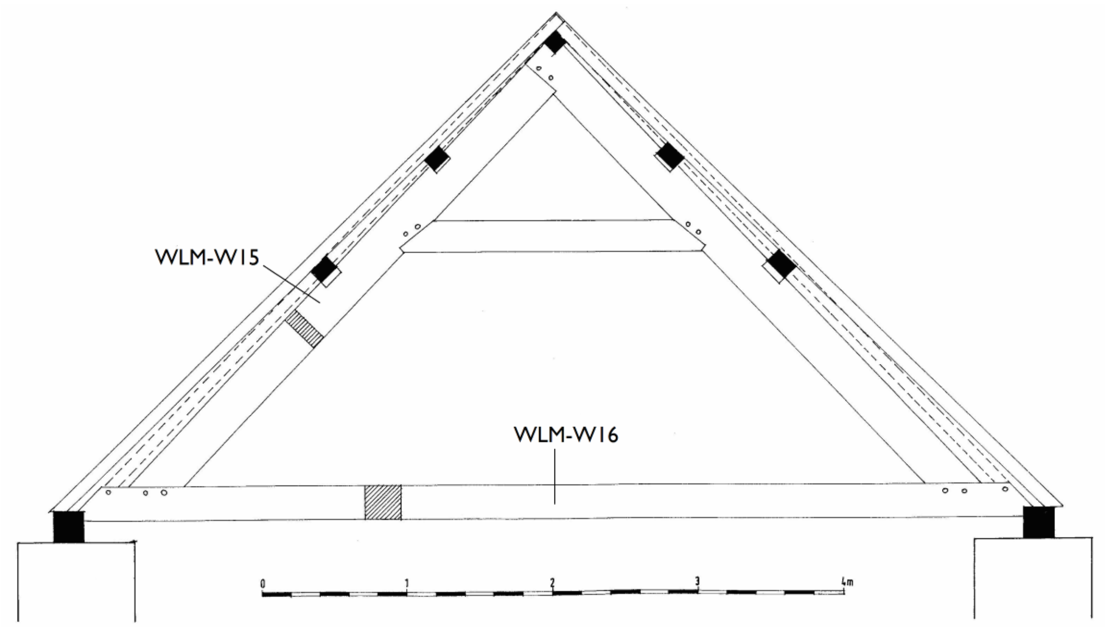

Figure 21: East range (south), truss 7 (south face), showing the location of samples WLM-W15 and WLM-W16

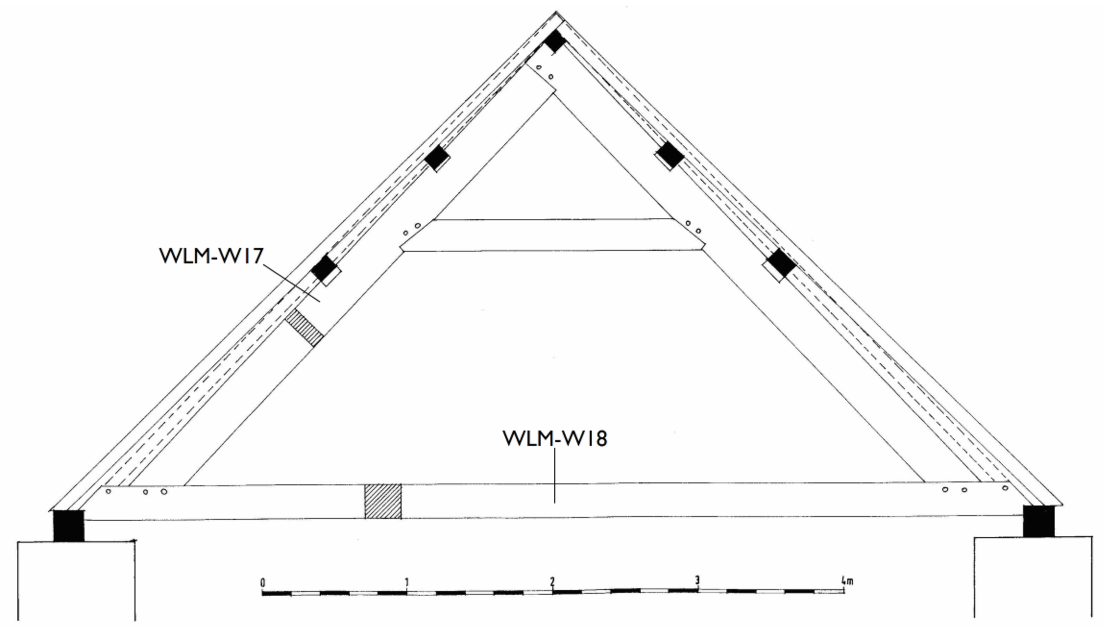

Figure 22: East range (south), truss 8 (south face), showing the location of samples WLM-W17 and WLM-W18

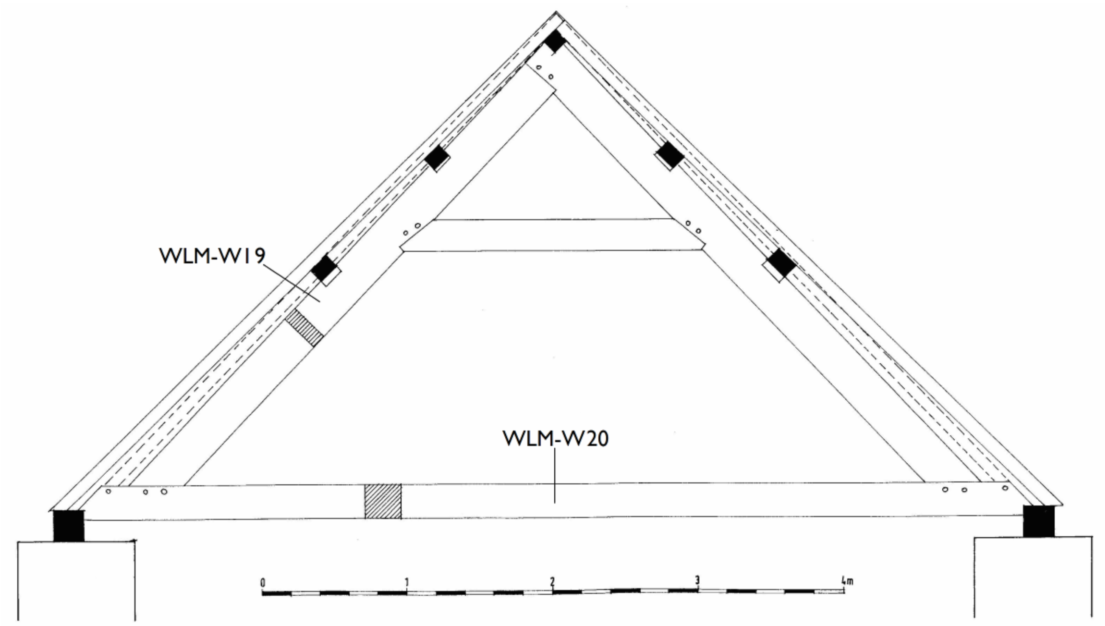

Figure 23: East range (south) (south face), truss 10, showing the location of samples WLM-W19 and WLM-W20

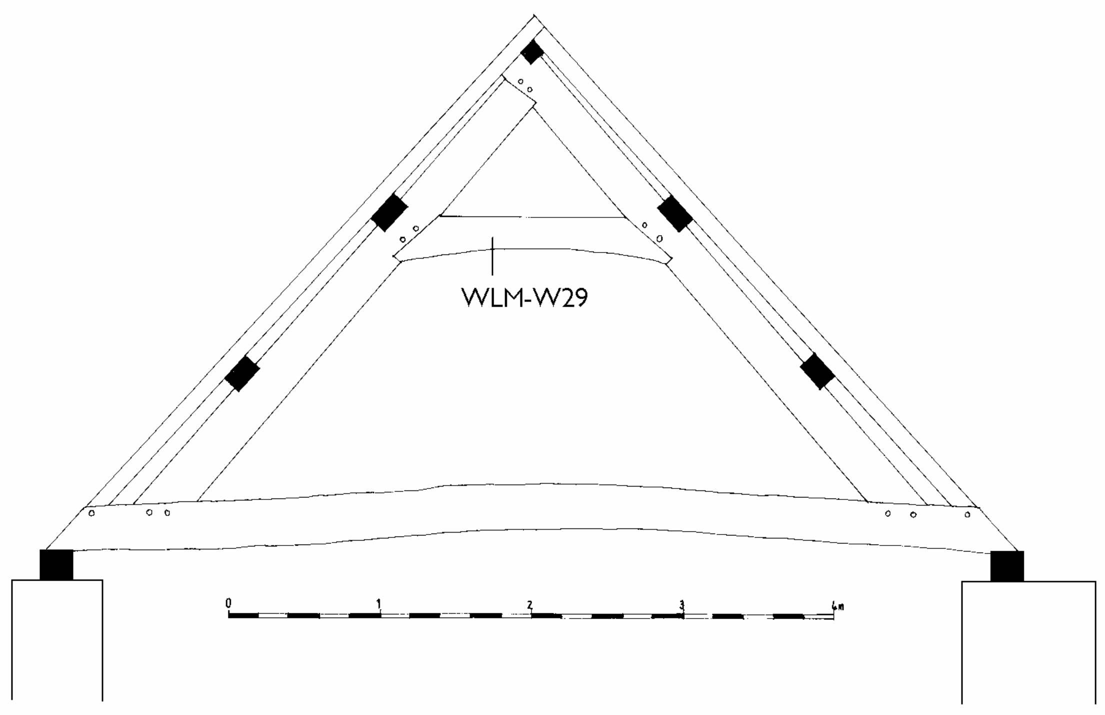

Figure 24: North range, truss 1 (east face), showing the location of sample WLM-W29

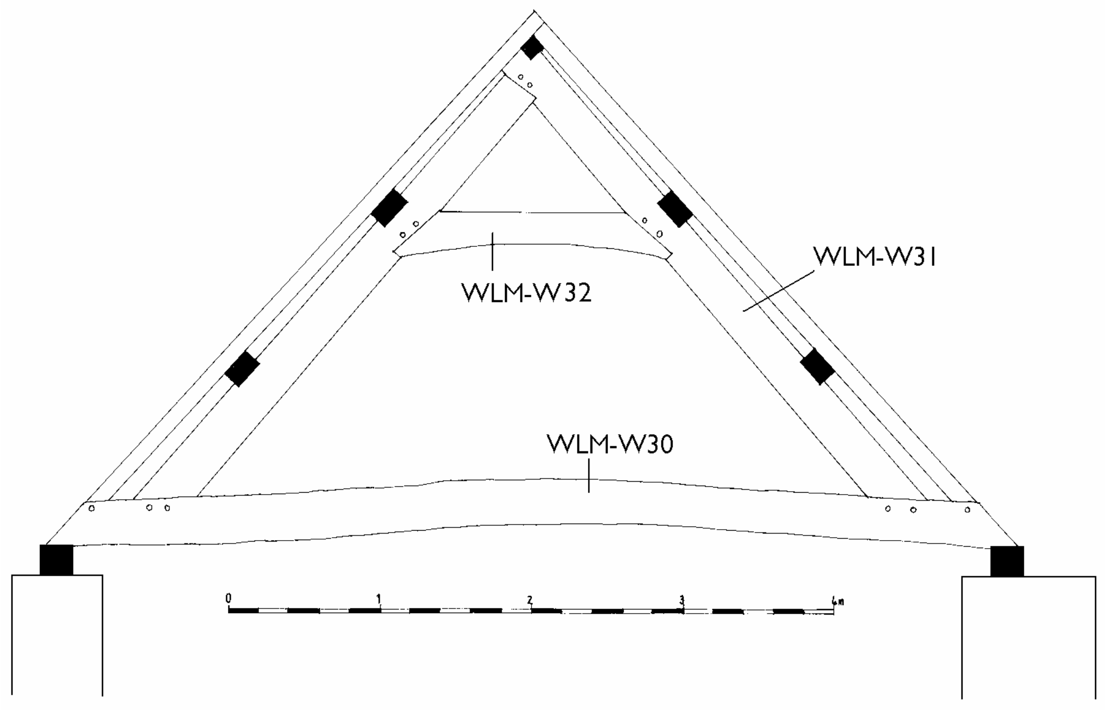

Figure 25: North range, truss 2 (east face), showing the location of samples WLM-W30–2

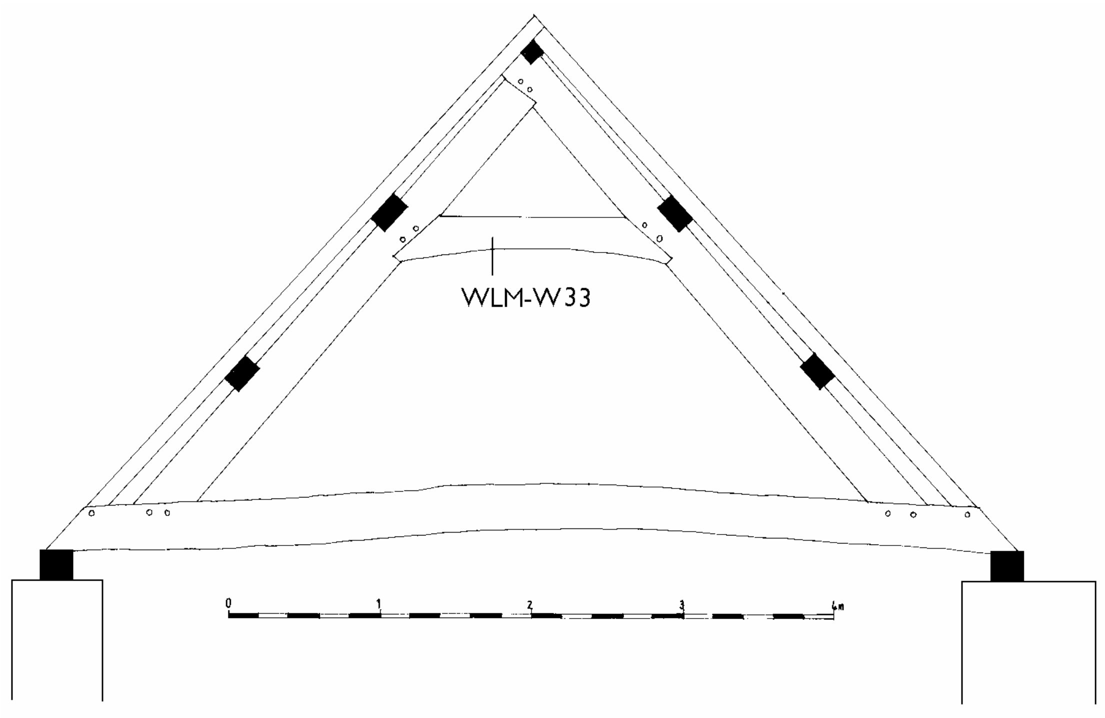

Figure 26: North range, truss 3 (east face); showing the location of sample WLM-W33

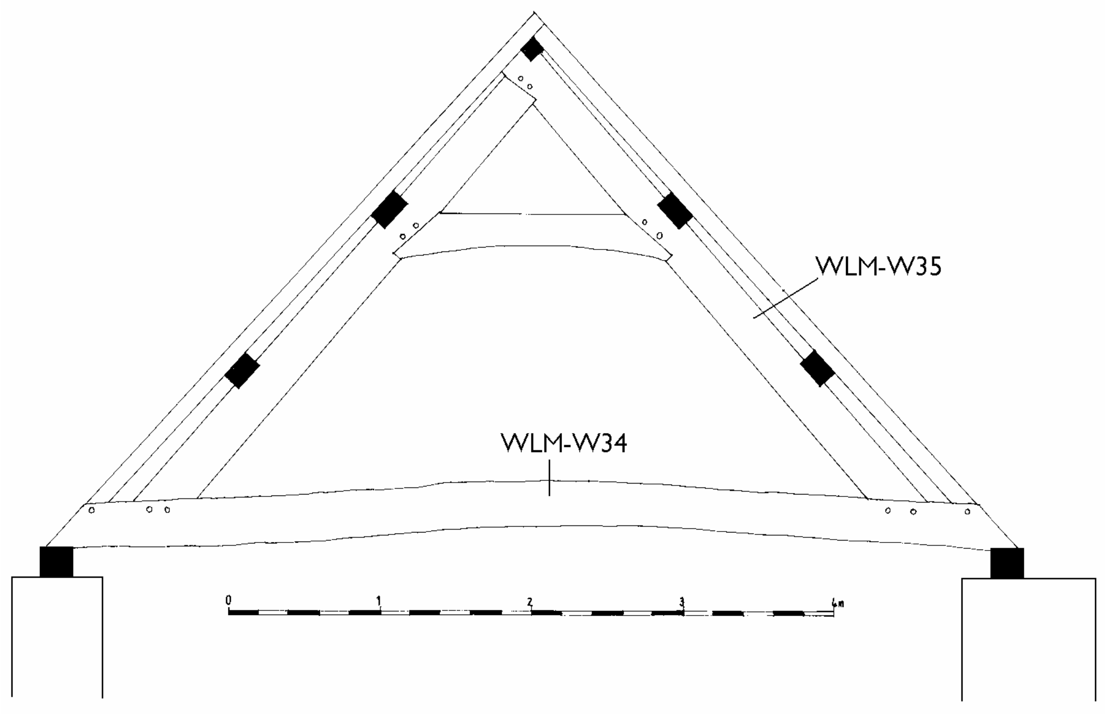

Figure 27: North range; truss 4 (east face), showing the location of samples WLM-W34 and WLM-W35

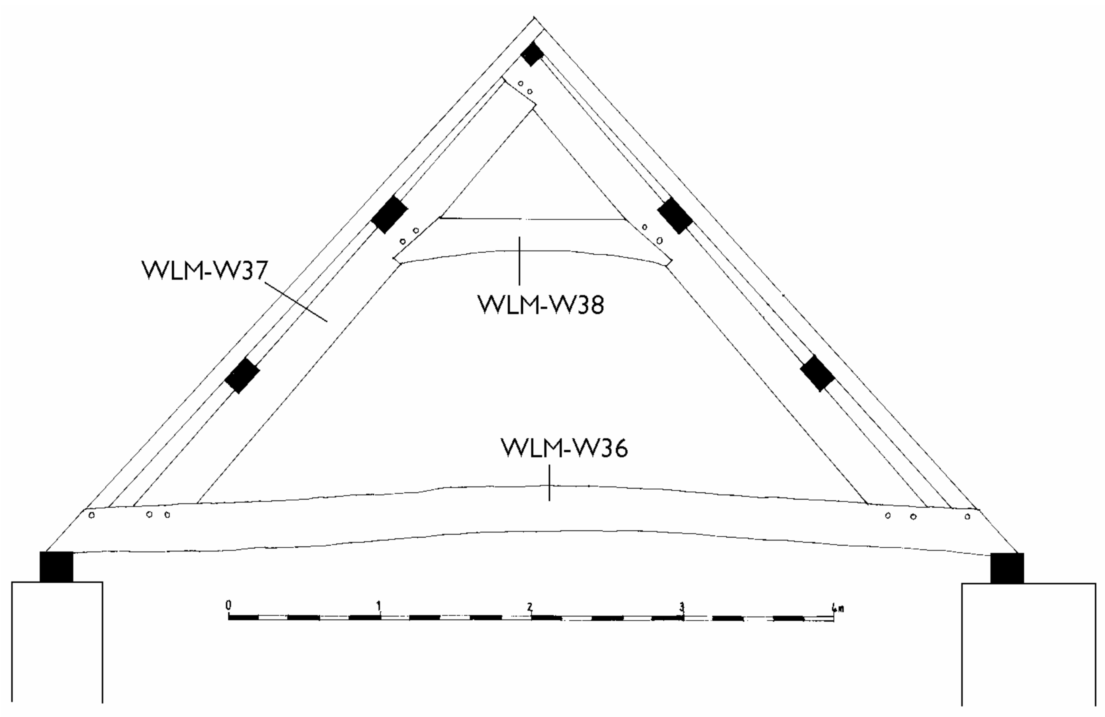

Figure 28: North range; truss 5 (east face), showing the location of samples WLM-W36–8

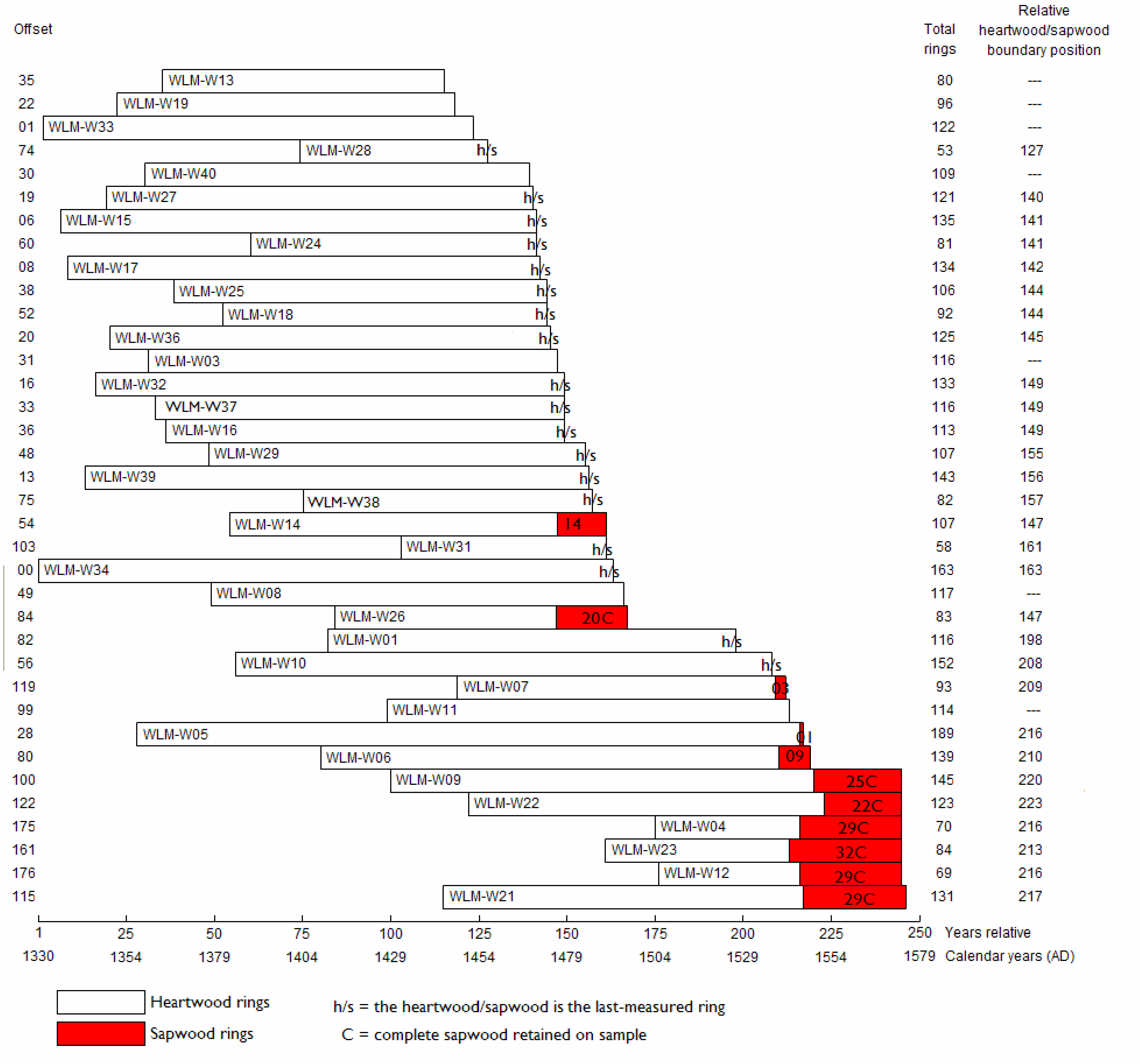

Figure 29: Bar diagram of samples in site sequence WLMWSQ01

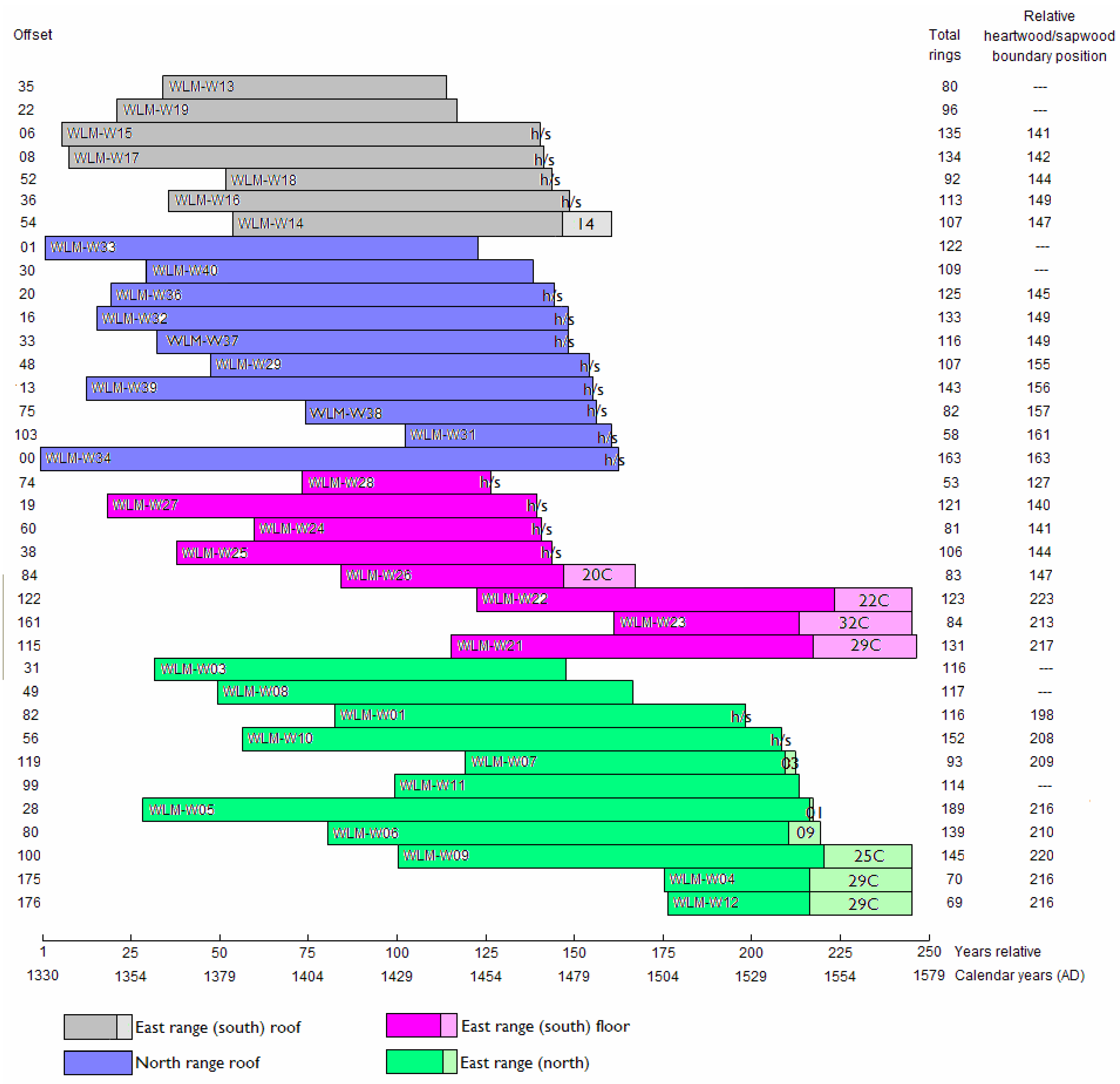

Figure 30: Bar diagram of samples in site sequence WLMWSQ01, sorted by area

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WLM-W01A 116
90 122 95 93 54 91 89 97 63 98 93 100 101 50 47 48 58 69 67 102
78 66 56 72 57 79 72 53 64 75 65 78 100 79 79 85 97 93 116 71
102 117 116 123 116 123 92 84 91 90 124 133 137 135 147 177 125 127 150 177
145 161 124 157 172 142 118 119 127 106 99 90 107 125 140 129 107 105 89 113
107 53 68 75 94 91 78 105 108 82 98 64 121 89 86 74 86 91 84 87
90 70 81 73 84 81 92 55 58 57 52 43 49 68 68 72
WLM-W01B 116
154 110 87 99 57 77 77 66 64 91 99 99 102 43 55 44 56 74 64 104
79 62 66 76 60 81 63 58 60 84 60 70 100 81 86 73 104 89 129 64
106 117 119 120 116 118 101 89 93 87 130 131 144 128 135 174 127 128 140 177
151 139 135 155 173 137 106 120 128 98 98 90 111 122 144 125 104 101 88 115
101 61 63 71 98 89 83 103 101 89 92 69 117 96 80 80 75 89 86 99
86 70 74 65 88 71 94 61 52 55 53 43 52 61 70 66
WLM-W02A 84
203 272 152 179 220 223 220 160 192 180 186 225 138 207 129 172 213 217 172 168
154 133 188 247 234 351 335 280 263 218 226 326 189 162 186 166 178 138 147 166
187 175 136 132 152 188 227 229 202 228 220 196 181 151 158 175 181 130 162 172
193 216 112 90 74 79 96 123 89 111 91 128 158 122 137 121 149 100 164 166
154 151 124 77
WLM-W02B 84
198 273 151 173 225 218 215 170 194 178 188 227 136 207 127 170 220 216 169 167
146 139 192 264 237 367 333 283 273 226 219 309 190 166 187 167 173 148 132 171
194 174 133 133 150 191 227 235 203 231 220 198 180 150 160 186 186 132 154 169
200 211 139 87 81 80 93 116 92 113 86 128 152 132 131 124 144 107 153 179
145 151 129 89
WLM-W03A 116
173 218 242 286 261 229 221 181 147 174 179 207 193 232 204 229 183 237 294 258
171 151 122 181 142 190 183 200 209 131 143 146 189 194 196 216 137 161 140 126
117 63 78 62 86 69 59 75 58 45 47 64 76 68 94 62 78 71 61 91
168 222 197 197 149 314 270 305 243 199 204 274 163 165 209 224 180 138 112 133
170 121 121 229 261 233 276 191 209 185 227 230 200 244 209 180 147 88 117 126
127 152 193 137 144 241 212 195 147 132 110 93 98 97 146 124
WLM-W03B 56
78 63 86 166 218 214 191 130 300 279 301 260 199 216 272 180 177 225 215 183
144 123 160 164 131 168 283 291 272 325 204 238 203 221 230 194 257 203 176 118
81 101 121 105 149 191 127 144 195 201 187 129 113 95 74 79
WLM-W04A 70
295 368 360 398 407 469 347 337 367 294 332 244 225 234 269 241 238 154 163 265
286 266 256 225 224 206 170 148 176 195 140 144 126 115 161 119 55 34 46 59
49 71 53 80 74 69 83 76 84 78 77 87 101 78 73 75 81 95 100 104
63 62 73 80 94 109 107 95 108 69
WLM-W04B 70
326 370 359 393 408 466 344 332 363 293 332 249 227 238 273 235 228 153 163 250
289 286 235 222 217 211 171 144 179 204 148 131 127 119 162 119 60 36 48 57
46 64 54 80 72 70 92 76 85 83 81 89 101 77 69 71 89 93 102 111
66 57 69 71 85 107 121 84 91 89

WLM-W05A 189
110 122 123 149 124 205 234 270 274 231 226 223 181 181 279 292 349 247 96 116
125 188 255 223 238 285 213 170 274 257 235 211 186 163 126 150 172 156 184 116
174 186 244 218 238 185 165 172 165 123 167 185 153 150 143 152 140 172 136 137
154 125 121 142 196 184 146 105 150 147 115 108 116 135 143 91 67 115 109 126
119 104 93 111 92 120 111 116 102 109 119 121 123 122 149 142 113 125 109 110
82 70 102 88 109 91 109 106 107 91 98 79 95 106 100 83 99 109 133 97
100 129 116 128 113 124 119 121 128 120 115 123 114 148 107 99 84 113 101 105
85 114 118 109 109 98 119 167 159 152 120 114 140 109 100 119 119 123 135 131
133 109 136 99 109 127 152 165 185 152 123 168 163 128 109 131 141 156 135 141
176 166 145 124 157 117 165 147 157
WLM-W05B 189
116 120 119 125 126 204 230 258 269 209 211 229 179 183 281 264 333 241 102 123
129 205 253 228 238 264 221 168 259 278 228 214 186 166 128 147 170 166 172 115
173 188 236 216 237 157 197 167 160 111 165 181 160 146 148 141 143 169 116 128
140 109 121 141 199 198 143 104 154 172 95 121 114 135 146 94 75 114 116 119
131 95 99 111 94 122 107 113 111 112 117 122 118 119 149 142 122 128 112 111
87 70 87 79 109 90 101 102 106 91 97 71 109 106 97 80 99 111 126 100
81 129 124 133 109 115 113 122 101 120 120 111 108 139 101 90 90 110 103 96
87 111 118 110 98 96 119 162 160 152 130 117 141 113 102 115 119 119 135 127
134 106 136 102 106 125 158 163 193 153 125 181 172 133 102 122 152 150 126 143
172 167 144 126 161 119 177 143 161
WLM-W06A 139
270 246 286 244 244 178 205 221 285 162 249 250 274 336 193 118 254 247 280 344
238 247 248 194 227 220 243 227 197 141 165 192 124 114 149 131 170 177 134 133
128 122 159 155 128 152 136 137 126 87 123 114 132 142 120 102 141 179 165 198
179 67 43 36 34 59 75 53 41 41 47 53 58 52 45 47 35 31 26 28
22 39 26 38 28 34 54 38 38 52 67 51 60 55 74 99 78 108 105 95
86 84 78 102 82 110 116 104 125 90 107 86 49 67 86 105 137 127 100 119
134 114 83 95 85 80 97 102 89 119 86 77 95 108 102 132 117 89 112
WLM-W06B 139
269 245 298 248 242 178 194 244 282 155 247 244 279 329 196 123 265 223 279 339
248 272 263 187 218 221 232 221 211 140 165 180 120 116 148 133 169 176 129 137
123 113 144 160 133 152 140 152 119 92 127 118 121 161 120 110 134 174 161 191
179 62 46 29 39 62 73 54 39 47 37 57 57 52 50 40 34 32 32 23
26 36 25 32 31 35 52 36 36 54 61 50 65 53 73 97 79 102 102 99
80 81 89 85 82 107 112 96 126 89 107 84 55 64 79 106 139 129 93 123
130 109 82 88 89 80 101 91 106 104 86 71 96 105 107 139 116 81 105
WLM-W07A 93
127 146 126 172 188 131 136 136 120 88 58 102 74 106 112 125 87 91 129 117
86 106 79 76 55 65 86 92 80 80 86 76 92 91 96 87 83 83 96 72
104 98 97 115 76 95 73 117 73 81 98 109 74 87 85 134 103 97 126 112
117 129 96 88 106 78 98 94 103 108 83 104 58 52 49 62 72 93 86 98
94 110 73 65 66 86 61 62 65 75 83 63 58
WLM-W07B 93
112 151 115 185 171 135 134 129 130 86 64 109 75 105 113 123 83 95 122 126
78 97 102 76 52 73 71 100 66 77 88 71 86 92 90 90 77 86 89 76
115 107 104 105 92 97 86 113 83 76 106 94 87 78 84 124 105 96 128 106
118 129 99 86 110 85 95 97 101 116 75 112 56 52 51 58 78 88 90 93
96 103 78 58 71 87 52 67 61 80 82 62 62

WLM-W08A 117
368 298 229 170 160 102 86 90 157 138 176 146 106 87 82 119 89 121 84 76
124 202 207 185 193 151 183 172 183 178 226 139 141 147 240 209 221 104 108 136
109 100 135 191 171 245 186 256 193 197 251 200 122 215 133 84 128 138 147 182
111 113 125 128 118 166 179 128 187 194 180 174 176 182 176 187 193 166 197 114
94 96 111 127 140 155 139 111 200 176 158 168 171 107 135 158 225 241 165 134
118 168 174 153 184 144 167 158 201 147 173 184 129 171 120 122 110
WLM-W08B 117
529 308 226 182 186 105 66 110 136 135 190 134 122 80 79 127 82 123 75 82
123 208 204 193 186 146 187 170 187 169 218 146 135 155 236 205 232 97 114 137
101 107 128 202 168 247 183 255 182 199 269 177 125 215 137 88 121 143 139 168
102 116 122 129 120 169 177 135 197 176 196 165 160 175 172 191 186 165 189 122
92 95 117 127 140 144 145 118 199 178 153 167 174 114 125 152 233 242 166 139
119 162 189 150 189 176 145 158 200 157 179 168 138 174 138 95 116
WLM-W09A 145
151 168 212 112 91 100 97 78 105 79 73 64 99 117 135 123 133 144 133 119
112 158 147 167 171 151 125 88 68 61 69 55 70 97 82 90 109 137 101 93
105 93 79 74 71 117 168 118 198 187 145 154 138 116 163 138 128 169 129 111
117 116 85 66 65 80 70 70 69 79 104 96 94 65 82 126 126 150 145 89
102 72 67 78 71 92 125 121 139 140 126 102 52 73 93 95 93 82 57 72
84 66 35 50 69 61 54 59 60 69 68 65 49 51 67 52 51 52 63 45
44 89 40 57 50 89 51 50 80 100 78 84 70 69 68 48 29 35 36 35
47 35 44 38 37
WLM-W09B 145
148 168 196 121 71 98 78 80 79 85 71 73 94 121 136 127 134 143 142 120
115 176 146 171 176 172 141 101 82 63 68 56 74 105 77 97 122 124 104 78
97 88 86 74 63 126 153 129 200 186 140 163 145 116 166 137 132 171 131 111
114 116 84 73 60 82 63 73 70 76 105 93 96 66 83 123 124 152 140 90
98 77 66 82 70 97 131 126 144 145 127 88 58 73 81 87 93 80 59 74
80 67 36 50 68 62 54 59 61 68 67 73 41 43 67 56 46 61 62 41
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31 35 47 37 33
WLM-W10A 152
140 154 151 148 137 124 127 138 152 142 186 127 205 183 271 175 188 177 164 187
132 123 153 139 139 116 114 101 126 169 125 137 120 106 106 121 183 143 150 100
144 132 132 167 146 134 141 109 84 115 136 99 103 89 100 87 93 111 100 96
98 96 106 112 100 97 118 123 88 85 93 75 72 61 65 61 86 66 92 85
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84 94 84 90 86 88 75 72 65 75 78 62 66 89 96 96 90 81 114 133
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85 77 63 82 105 83 63 99 96 112 80 110
WLM-W10B 152
145 160 151 145 132 141 135 136 164 149 179 130 184 224 235 197 199 167 164 174
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140 135 130 167 165 111 144 101 87 117 133 111 120 89 92 82 92 102 103 97
92 97 114 105 102 92 120 123 88 85 93 75 67 60 68 59 88 64 97 86
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88 92 87 91 82 92 75 74 65 75 74 69 69 85 89 98 89 80 118 133
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87 72 67 80 103 84 66 95 95 115 92 93

WLM-W11A 114
354 290 343 368 223 360 419 441 487 344 285 335 388 301 367 422 409 395 394 421
533 385 441 421 382 501 358 426 402 314 270 173 252 341 397 326 347 412 391 362
289 279 298 161 135 195 339 314 275 297 260 196 182 112 131 152 210 231 256 155
154 185 161 189 135 173 171 198 169 182 192 212 175 120 145 221 218 260 208 201
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WLM-W11B 114
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507 377 462 417 367 505 359 410 410 329 277 179 236 347 393 328 328 410 378 354
298 287 297 157 139 194 352 321 278 299 251 200 188 120 128 152 199 242 262 150
167 183 158 188 141 170 164 194 170 188 196 211 171 122 144 218 223 253 208 201
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122 110 80 65 73 73 84 113 121 112 160 112 67 86
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217 281 401 270 234 211 259 337 279 270 246 260 334 239 262 142 115 129 151 165
194 128 178 144 174 130 108 130 141 161 109 74 99 124 130 94 71 85 105 113
143 142 113 96 114 128 114 120 90 102 80 101 95 87 83 65 71 74 75 53
48 58 66 83 108 103 114 102 101
WLM-W12B 69
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173 151 156 158 162 133 113 122 144 153 107 80 106 107 125 95 71 82 113 107
144 146 111 98 115 127 114 117 99 94 81 103 93 89 76 66 75 68 69 59
45 64 60 87 112 100 112 105 97
WLM-W13A 80
283 230 257 246 204 144 184 233 221 219 177 151 119 160 169 158 137 184 215 262
190 279 288 242 228 223 230 196 181 190 143 164 110 183 198 184 217 163 173 152
142 141 136 128 153 144 163 126 172 126 127 73 128 157 145 146 136 164 170 145
92 81 130 151 191 185 193 193 138 239 180 170 170 263 165 202 182 170 170 138
WLM-W13B 80
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175 290 296 238 228 232 227 208 175 185 150 168 109 199 204 203 214 164 175 149
141 145 138 118 155 146 172 122 174 107 136 68 130 157 147 139 153 146 181 143
91 81 129 151 187 190 189 190 141 225 197 154 183 251 164 200 182 169 178 185
WLM-W14A 107
280 176 176 114 155 165 135 88 142 137 168 159 184 93 172 228 254 220 217 239
245 191 156 143 125 186 180 195 209 258 168 160 77 150 193 129 184 223 248 234
155 108 91 105 201 292 183 172 207 181 274 314 289 313 335 194 175 198 115 129
256 292 187 229 200 181 94 125 116 138 157 136 125 104 72 64 83 97 106 146
114 110 128 180 161 128 155 164 86 68 83 91 142 122 118 88 87 68 60 86
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WLM-W14B 107
293 177 180 127 156 160 135 97 155 127 172 156 196 103 176 234 254 221 241 239
229 190 170 157 126 193 183 188 204 273 170 159 84 152 193 129 198 217 265 237
147 111 88 106 205 291 190 171 209 179 278 311 289 324 338 189 184 193 121 134
255 291 203 220 196 181 92 125 114 132 162 132 120 105 77 71 71 103 98 150
115 115 135 166 154 134 156 166 84 60 88 93 139 127 124 83 89 65 54 87
62 40 55 63 61 68 85

WLM-W15A 135
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95 80 77 110 122 124 119 165 132 116 66 86 96 82 87 71 68 53 57 66
72 38 56 94 126 99 108 65 76 47 73 47 78 82 80 53 79 81 80 55
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73 83 78 72 57 72 52 58 92 85 81 68 69 82 63 72 74 90 98 103
86 81 75 61 50 54 80 61 78 77 83 107 97 90 76
WLM-W15B 135
265 299 273 255 229 230 241 198 170 139 95 77 140 256 250 202 132 126 141 135
142 140 148 165 129 142 123 188 148 151 168 145 135 98 74 106 123 114 144 163
88 82 77 115 119 129 123 170 125 109 77 83 90 82 79 76 71 55 61 62
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91 78 77 49 56 57 73 61 75 70 95 115 105 83 73
WLM-W16A 113
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149 156 162 159 122 121 117 182 212 223 235 152 186 212 277 249 218 310 240 179
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WLM-W16B 113
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156 157 168 165 123 119 118 179 216 223 238 151 198 216 277 246 213 310 244 182
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179 205 187 216 162 186 147 195 205 188 182 193 128 89 159 185 229 248 185 134
223 207 180 239 218 137 62 97 72 170 197 144 103
WLM-W17A 134
228 214 228 233 256 234 207 131 99 119 205 259 182 127 108 99 148 181 178 178
144 146 113 120 110 136 187 176 234 195 129 86 70 94 104 102 153 141 68 87
69 96 128 137 141 168 145 125 83 88 123 130 123 88 84 75 95 89 99 38
84 93 129 103 115 103 87 64 55 58 80 78 74 55 79 103 76 76 49 88
77 83 117 119 150 97 71 48 51 73 85 105 91 73 103 83 85 92 75 82
104 89 82 81 59 53 117 96 84 84 61 73 79 75 89 88 96 75 77 69
46 52 46 66 83 63 92 92 108 125 90 65 75 68
WLM-W17B 134
239 210 221 243 254 231 212 137 103 123 196 257 180 131 98 100 138 188 186 176
149 139 100 125 116 124 192 178 222 198 133 79 78 99 100 102 158 137 68 82
67 103 125 139 142 160 141 130 79 87 122 126 130 87 82 75 92 86 108 44
80 93 129 103 113 105 83 60 58 58 84 75 68 67 74 101 82 74 64 81
75 85 109 104 151 95 69 64 46 71 91 109 93 70 108 79 84 95 72 80
104 88 90 78 56 55 105 90 80 86 57 71 71 81 80 87 82 78 73 74
50 47 45 68 89 58 90 94 109 123 98 59 80 72
WLM-W18A 92
138 168 244 142 228 234 210 210 189 147 154 211 189 195 208 251 229 311 373 254
275 212 265 221 261 167 205 224 205 224 200 198 199 192 160 167 231 128 167 190
226 249 168 115 124 170 172 219 177 222 196 130 165 166 191 166 137 122 144 178
115 132 175 140 131 147 122 143 144 132 144 168 190 201 172 157 123 101 133 117
140 127 130 115 135 185 180 171 182 166 92 102
WLM-W18B 92

152 174 230 148 222 299 178 217 195 148 163 203 209 203 227 237 226 308 374 260
274 218 260 209 256 173 212 216 224 227 185 205 198 183 163 169 236 140 157 194
264 232 174 115 139 155 191 221 174 247 189 112 174 169 188 170 126 124 147 176
113 137 174 132 135 159 123 155 139 127 139 170 195 212 170 167 112 101 123 111
142 124 130 117 137 181 171 169 184 159 92 100
WLM-W19A 96
472 587 328 283 324 292 202 124 84 135 157 188 216 199 198 168 94 57 68 108
174 180 220 206 157 137 144 185 176 165 165 209 249 149 135 159 168 153 139 162
150 174 158 124 137 89 132 129 207 146 186 165 145 130 96 100 118 141 133 97
116 132 107 103 70 105 109 82 120 134 118 157 109 86 89 99 139 172 147 106
149 128 136 163 154 155 163 118 159 139 129 105 156 168 136 164
WLM-W19B 96
435 568 338 275 325 267 193 132 70 129 164 188 198 206 194 165 93 59 60 105
146 193 219 202 152 136 148 181 176 159 178 221 251 142 135 148 181 149 136 167
147 169 157 135 135 99 133 135 199 155 188 174 146 138 99 100 115 143 128 100
108 131 107 102 70 105 105 87 119 142 107 158 112 88 83 103 144 160 147 112
147 126 135 166 160 168 165 130 156 131 143 108 158 147 147 156
WLM-W20A 80
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137 152 123 64 100 93 45 59 71 92 125 125 97 115 88 95 99 132 157 147
171 140 87 121 91 125 199 214 190 222 213 151 147 159 197 122 176 210 132 110
WLM-W20B 80
123 172 241 172 145 147 105 130 200 157 219 240 216 249 269 271 303 274 255 343
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131 161 128 63 107 81 33 63 71 95 118 128 106 111 81 102 98 134 152 142
162 138 103 121 96 118 198 215 186 229 208 157 137 161 195 143 160 211 135 94
WLM-W21A 131
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165 257 351 271 215 210 245 169 151 141 184 173 196 191 202 195 153 88 117 134
145 162 187 133 119 129 100 64 64 90 108 149 150 133 139 129 113 102 74 112
149 189 160 160 157 139 121 100 105 97 113 111 115 122 92 91 76 63 66 49
69 73 61 68 86 77 78 63 84 78 97 87 105 84 135 138 103 105 87 126
97 107 91 79 63 62 70 59 68 59 69 54 67 76 54 69 59 62 62 79
69 44 66 58 66 68 72 65 74 67 86
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297 263 374 355 319 248 223 333 277 282 183 208 207 176 185 172 173 234 220 158
163 255 344 269 222 200 247 174 153 138 184 173 199 192 205 185 150 89 120 129
142 163 188 135 123 124 104 66 74 78 109 145 144 147 131 130 106 100 75 110
154 189 169 151 167 134 120 103 106 93 110 118 113 124 92 90 78 58 56 50
69 72 61 69 85 75 74 68 82 82 96 88 100 85 135 142 105 100 90 113
106 108 87 81 61 59 70 67 61 70 62 55 67 72 58 65 58 68 60 78
70 46 64 56 58 74 72 68 75 72 79
WLM-W22A 123
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124 84 77 146 209 187 207 188 124 151 151 126 160 137 182 178 117 141 153 92
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78 55 68 83 91 96 105 79 44 35 29 41 34 77 78 70 89 131 108 91
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55 27 39
WLM-W22B 123
56 58 56 39 71 54 59 52 48 52 83 100 113 84 125 182 180 137 152 185

121 80 76 146 198 198 206 190 127 149 152 125 160 139 181 170 113 144 156 101
96 76 71 104 85 84 95 81 83 68 38 35 88 94 109 94 98 126 106 100
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110 128 40 27 16 28 22 25 27 26 39 34 26 24 28 26 44 42 54 43
44 33 32
WLM-W23A 84
266 230 155 282 254 357 288 300 283 231 115 105 73 277 399 394 343 287 264 204
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151 66 106 138 150 151 157 179 180 124 73 87 135 172 177 148 106 162 74 72
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122 120 133 67
WLM-W23B 84
257 224 136 289 243 367 274 298 277 221 128 109 77 269 397 394 342 287 267 208
167 127 171 226 241 231 219 199 180 201 189 119 75 224 225 240 190 143 162 186
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58 68 104 121 152 139 176 97 141 120 213 170 196 146 64 52 39 77 83 123
143 106 135 71
WLM-W24A 81
114 110 93 103 110 111 95 82 99 109 155 161 135 155 144 155 122 114 147 199
164 173 169 179 194 159 126 155 161 125 154 143 154 140 134 64 111 123 159 186
142 175 154 122 140 141 87 112 105 110 127 122 97 111 146 146 124 150 132 119
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108
WLM-W24B 81
112 118 87 81 100 107 114 98 76 105 146 159 148 158 144 161 128 96 141 202
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125 109 130 150 119 123 125 133 102 79 76 99 109 104 90 86 90 164 139 119
98
WLM-W25A 106
157 138 104 108 140 111 200 257 157 144 142 165 170 173 145 149 195 145 153 162
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92 116 122 118 128 104 120 115 79 120 96 71 85 80 70 80 109 77 72 135
104 87 88 89 80 105 94 106 93 115 83 50 85 75 111 101 106 106 102 142
140 121 143 129 79 63
WLM-W25B 106
189 137 111 105 138 111 199 257 157 144 143 165 167 174 151 148 193 146 141 160
141 149 130 132 97 126 133 105 131 95 125 107 111 139 77 116 91 83 103 115
106 119 112 105 121 177 133 112 85 84 85 68 82 118 105 131 103 36 66 63
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125 120 143 139 65 86
WLM-W26A 83
148 161 142 147 180 117 113 173 146 140 140 91 125 119 150 108 106 92 102 85
96 138 115 123 148 105 118 132 91 142 192 142 151 124 108 117 125 118 121 151
153 157 161 198 168 139 184 157 165 185 164 164 155 192 184 200 177 187 160 129
134 162 189 118 126 103 114 128 109 107 110 99 136 126 146 123 150 199 124 131
104 93 99
WLM-W26B 83
154 163 138 157 176 116 115 170 148 138 142 89 127 122 145 112 102 91 103 84
112 137 119 122 141 115 111 127 98 130 201 144 150 128 105 119 125 117 124 146

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132 146 189 119 120 106 118 141 95 107 116 92 131 132 145 133 142 171 153 120
101 104 108
WLM-W27A 121
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178 133 106 152 133 183 221 232 220 154 225 147 143 159 169 227 164 268 216 167
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97 103 101 98 107 80 68 42 61 72 67 68 79 103 89 97 37 51 67 77
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118 101 95 119 124 115 121 122 104 106 45 53 80 86 94 96 102 105 113 105
81
WLM-W27B 121
137 131 158 129 155 149 174 240 185 153 161 129 170 171 180 176 166 159 177 183
202 146 95 158 125 180 223 224 219 163 223 154 129 148 144 224 166 267 212 172
127 102 93 89 87 110 99 96 67 94 112 139 146 106 93 76 86 66 48 69
97 102 97 100 103 75 70 42 74 62 82 61 88 98 93 89 34 55 71 68
106 122 124 128 99 107 109 97 96 102 92 96 88 54 69 74 85 100 117 125
119 96 97 120 129 113 119 127 105 105 48 71 78 92 87 99 101 100 123 100
92
WLM-W28A 53
205 176 161 157 183 204 252 203 169 185 180 167 150 248 217 175 251 192 203 203
208 124 98 136 183 240 213 200 207 180 273 210 183 196 199 169 199 207 161 168
236 213 148 189 183 167 163 139 142 219 212 202 216
WLM-W28B 53
203 179 161 145 188 208 278 176 186 197 166 169 155 237 229 187 238 190 213 200
209 116 100 134 174 246 213 207 216 180 269 214 193 195 191 167 208 194 162 166
237 196 148 181 194 175 172 142 157 214 254 197 222
WLM-W29A 107
113 106 139 160 145 131 160 119 122 107 109 120 117 108 106 70 112 104 115 81
116 118 166 95 107 127 108 99 58 80 84 93 96 94 99 111 89 90 62 104
98 93 111 96 137 113 76 50 61 102 138 161 137 132 104 96 120 115 114 119
92 74 97 79 71 79 108 107 101 136 91 114 86 72 122 92 113 99 113 94
84 69 57 66 112 126 97 108 115 145 128 107 122 137 88 92 96 107 147 115
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108 119 158 90 108 123 109 100 57 78 86 79 94 95 100 109 88 93 58 106
93 83 105 109 138 102 85 49 58 106 139 160 128 128 107 101 110 111 122 121
94 83 88 82 68 82 98 109 102 124 82 108 93 69 117 93 110 91 111 98
97 76 56 67 119 129 105 93 122 133 145 92 127 132 104 84 88 105 146 112
114 120 94 75 59 94 102
WLM-W30A 118
193 248 221 230 180 165 213 194 194 171 111 84 74 77 49 86 69 98 100 95
117 79 71 79 76 72 64 55 61 42 61 65 64 69 95 81 90 56 62 89
72 75 70 74 50 41 42 44 26 35 31 24 42 33 38 53 61 63 59 81
96 108 127 159 156 206 174 128 79 145 116 134 91 78 107 131 87 153 101 129
179 171 138 147 162 129 149 169 136 145 139 145 94 104 103 97 141 124 127 137
153 173 131 138 117 124 91 97 78 115 138 130 118 125 148 106 91 85

WLM-W30B 118
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121 75 75 76 79 72 65 55 64 42 64 65 62 71 97 83 84 56 69 85
71 78 69 77 46 41 48 37 34 31 28 31 43 36 33 51 56 57 67 78
108 105 120 167 158 203 171 123 85 148 111 125 104 75 112 132 97 153 101 135
172 169 143 152 162 133 155 164 135 147 145 144 90 108 101 99 143 123 125 142
143 166 134 132 119 125 92 98 79 118 135 136 112 133 145 106 98 94
WLM-W31A 58
307 253 260 273 242 317 263 255 342 265 293 370 352 315 380 355 435 347 415 361
368 407 328 332 381 368 311 301 312 368 393 286 351 379 420 423 404 397 376 242
208 220 342 344 275 255 427 316 310 329 268 298 225 295 371 300 316 411
WLM-W31B 58
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354 405 325 331 382 370 324 303 301 375 384 301 334 390 425 430 403 396 387 232
227 216 338 347 270 262 415 325 301 328 277 292 227 290 379 304 334 380
WLM-W32A 133
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WLM-W32B 133
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109 89 75 94 86 102 62 90 102 135 113 116 158 138 134 70 96 81 89 117
114 113 111 97 86 59 66 90 72 112 121 126 119 82 60 55 79 101 105 98
121 104 107 136 129 108 155 137 103 93 94 86 112 130 119 120 126 108 135 110
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WLM-W34A 163
142 230 261 161 131 176 175 143 191 210 169 164 239 149 146 93 93 129 185 235
161 177 157 152 148 159 155 124 86 94 80 107 58 122 126 114 72 102 94 68
47 62 90 73 91 89 56 65 77 76 50 71 87 102 113 101 96 90 60 59
42 43 39 44 39 41 28 31 45 44 55 44 41 48 42 42 34 28 34 47
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48 55 81 54 75 73 90 113 130 81 77 80 75 70 98 105 105 96 96 119
80 60 76 125 125 98 90 80 56 67 33 42 67 73 102 73 86 95 102 71
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WLM-W34B 163
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162 171 163 152 132 153 157 132 82 100 79 111 59 117 136 114 92 108 97 68
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50 58 81 55 73 68 95 114 137 75 82 81 77 61 106 95 108 99 97 114
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WLM-W36A 125
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WLM-W38A 82
97 75 94 87 117 116 118 130 144 99 103 60 88 78 88 93 91 116 120 88
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166 123 137 146 130 106 68 90 87 97 103 98 113 98 79 65 69 135 118 117
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58 75 77 74 82 77 70 80 70 72 88 77 83 79 85 63 53 51 58 58
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67 72 66
WLM-W40A 109
232 323 313 324 374 355 341 361 271 288 272 246 297 335 402 266 297 183 180 166
210 193 195 219 227 154 147 120 119 134 93 114 110 85 80 74 109 95 100 127
133 153 137 182 182 144 128 138 135 138 154 122 126 120 71 78 50 76 70 54
62 84 118 130 113 44 81 91 89 168 112 119 152 80 81 81 85 113 91 62
96 68 58 72 130 101 85 92 127 139 100 126 113 154 113 116 109 101 77 74
99 52 85 84 89 109 138 144 171
WLM-W40B 109
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

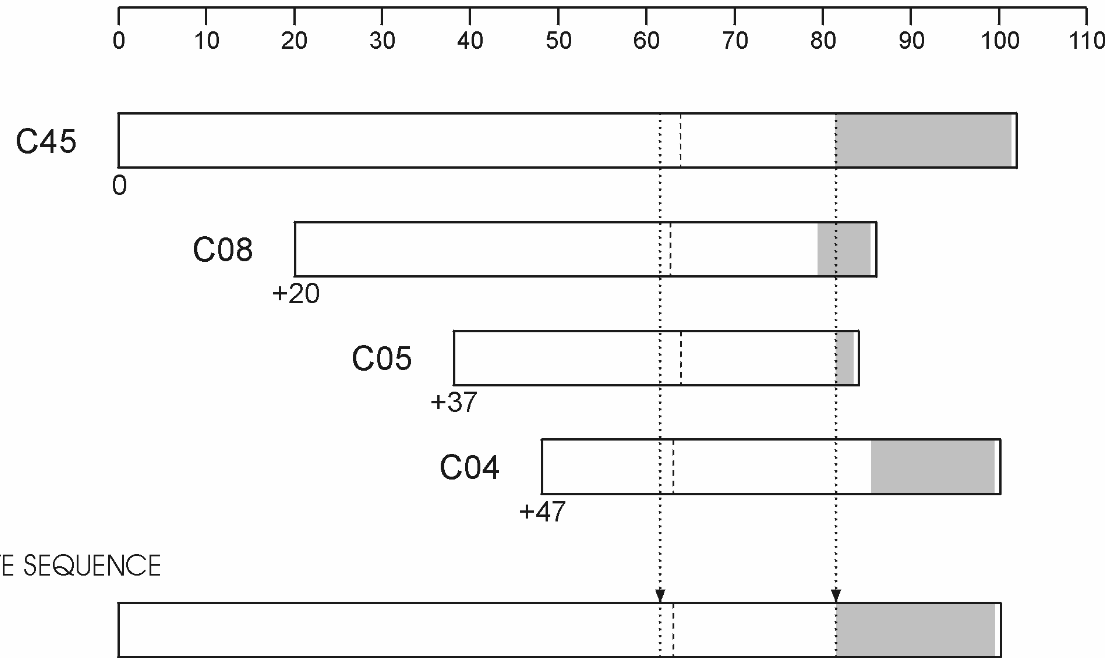

Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

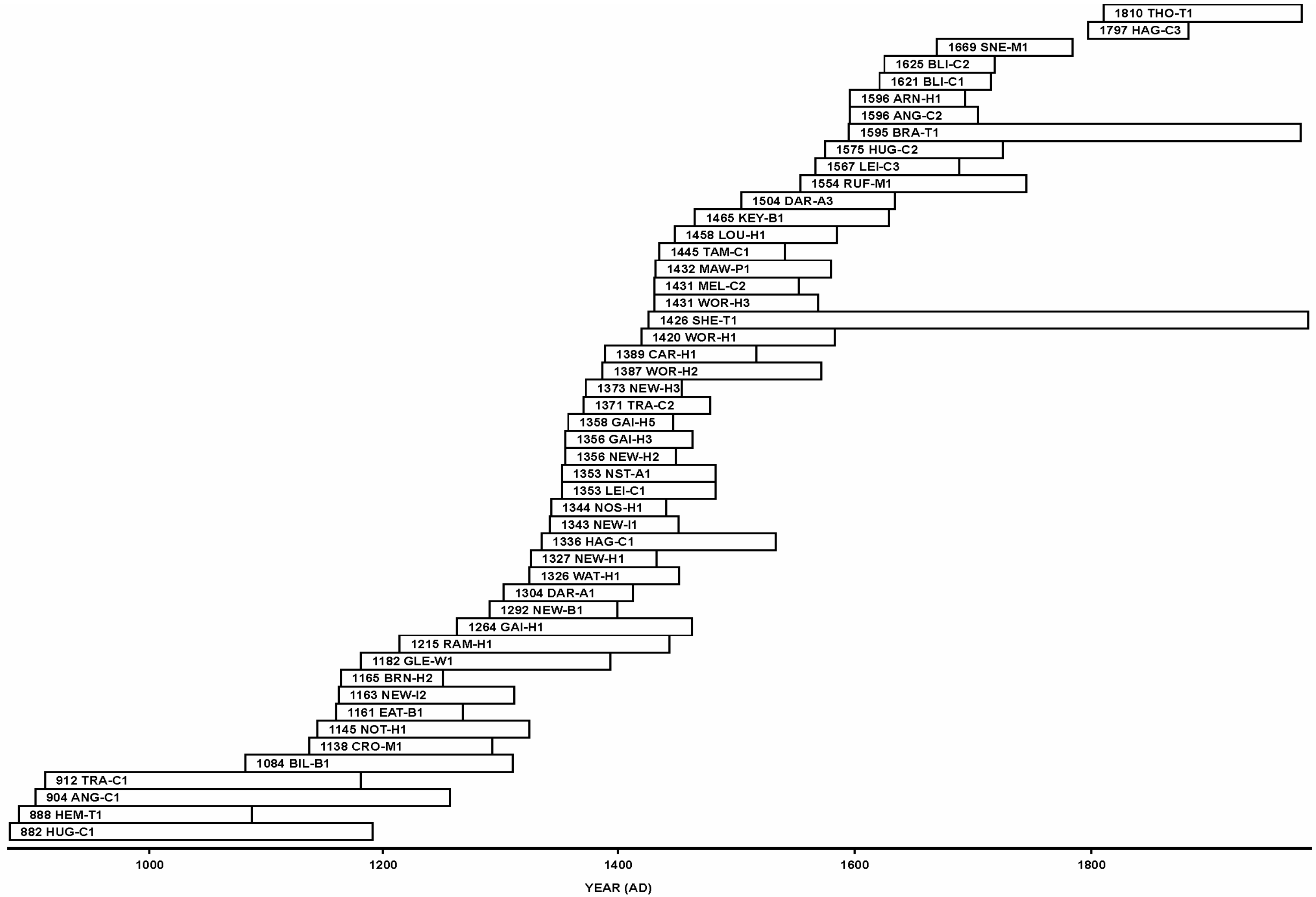

Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

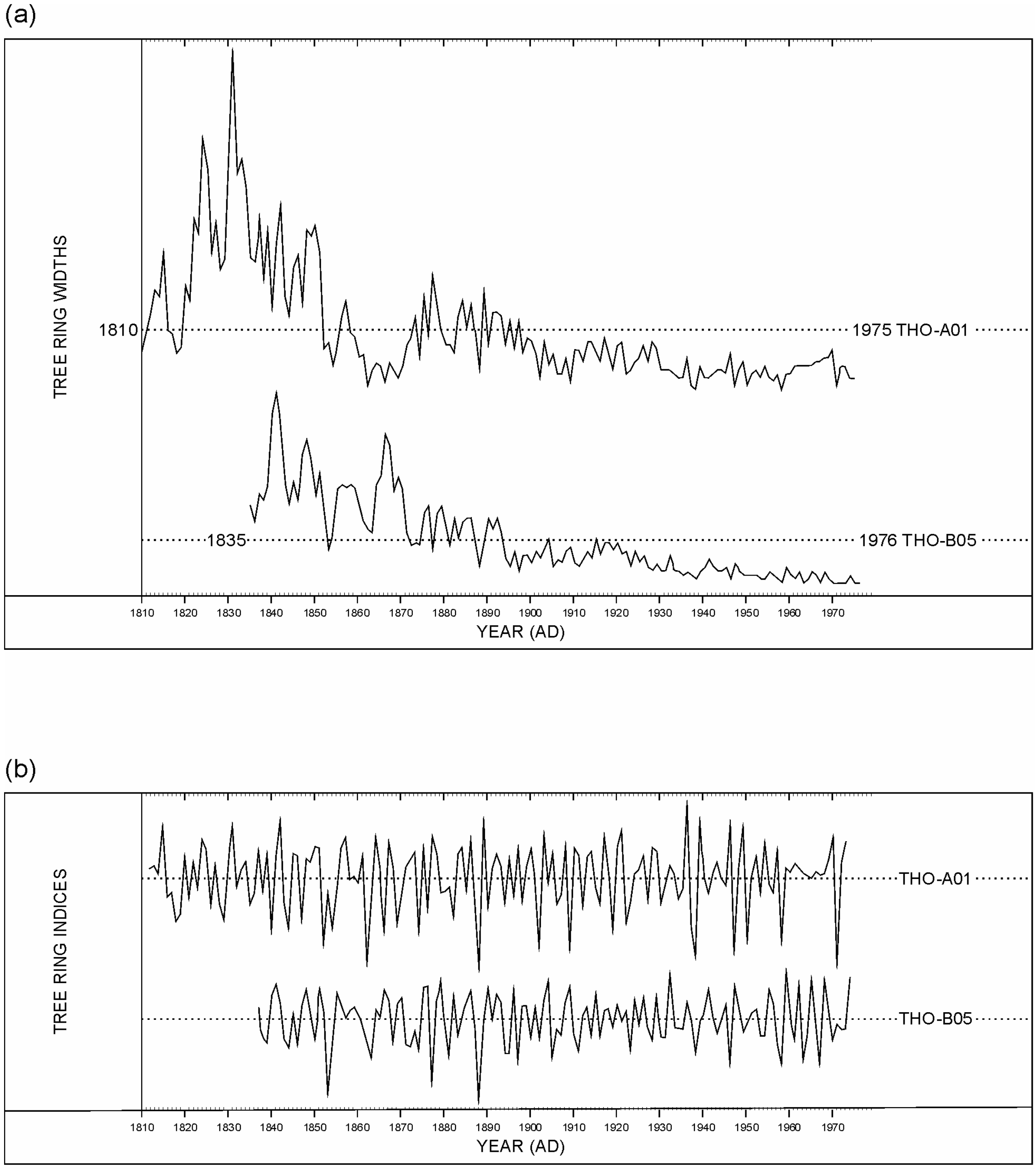

Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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