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Summary

Sixteen samples were obtained from two areas of roofing to the Keep, more commonly known as the "Little Castle", at Bolsover Castle, Derbyshire. This analysis produced a single sequence consisting of all sixteen samples, this being 218 rings long. The sequence was dated as spanning the years AD 1532 to AD 1749. Interpretation of the sapwood, and the heartwood/sapwood boundaries, on the samples would indicate that the timber used in both areas of roofing was felled in AD 1749.

It is known from documentary sources, and the stylistic information supports this, that the Little Castle was built in the early seventeenth century. Thus, a date such as AD 1749 for the timber of this roof is substantially later than that of the early seventeenth century previously ascribed to it. Such a date is, however, consistent with general repairs known, from documentary sources, to have been undertaken at Bolsover Castle in *c* AD 1750.

Keywords

Dendrochronology
Standing Building

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The Little Castle, Bolsover

Introduction

Bolsover Castle, an impressive grade I listed structure standing on a ridge east of and visible from the M1 motorway (SK 471706; Figs 1 and 2), has a long history. The earliest castle at Bolsover was of late eleventh-century motte-and-bailey type built by William Peverel, the bastard son of William the Conqueror. It reverted to the Crown in AD 1155. A stone keep was built between AD 1173 and AD 1179 with a curtain wall being constructed at about the same time. The medieval fortifications had fallen into ruin by the end of the fourteenth century and the site passed in and out of Royal hands throughout the fifteenth and sixteenth centuries until AD 1553. At this time it was granted to George Talbot, later Earl of Shrewsbury and husband of Bess of Hardwick.

Between AD 1608 and AD 1640 the castle was entirely rebuilt by Sir Charles Cavendish and his heir, William, the first Duke of Newcastle. In the first stage of reconstruction, between AD 1612 – 21, a new Keep, usually known as the Little Castle, was built in a romantic medieval style with angled turrets and battlements; the design is attributed to Robert Smythson, who died in AD 1614, and his son John. In its late-Elizabethan early-Jacobean context the Keep is a quixotic concept, rare, but not unique. It is small, but lavishly decorated, and to be seen perhaps as a retreat rather than a dwelling. It stands on a precipitous promontory above the valley below, and proud of the other buildings on the site, built up on its own pedestal, and surrounded by an enclosure wall and gardens.

To the south west of the Keep (see Figure 3) Sir William Cavendish added the Terrace Range overlooking the valley below with views to the hills beyond. This range contained a great hall, state rooms, and long gallery etc, and all the other accommodations expected in contemporary great houses. The design of the Terrace Range is attributed to John Smythson. Its' completion, and that of the riding school adjoining it on the south eastern side, and the subject of previous tree-ring analysis (Howard *et al* forthcoming), fell to his son Huntingdon Smythson. It would thus appear that all works at Bolsover Castle were complete before the start of the English Civil War.

Sir William Cavendish supported the King, Charles I, during the Civil War and when, after a siege, the castle surrendered to Parliament in AD 1644 it was slighted. How extensive this damage was is uncertain.

After the restoration of the Monarchy, when Sir William took control of the castle once again, repairs were commenced. However, the castle was stripped again from AD 1751 to furnish Welbeck Abbey nearby which then became the principal residence of the estate. By the later eighteenth century the Terrace Range in particular was roofless and in ruins, though the Keep and the riding school were maintained. Bolsover Castle was granted to the nation by the seventh Duke of Portland in AD 1945 since when it has been in state care.

The Laboratory would like to take this opportunity to thank Richard Sheppard of Trent & Peak Archaeological Unit for his assistance in the interpretation of the timbers, his information from documentary sources, and particularly for his drawings. The Laboratory would also like to thank the English Heritage staff at Bolsover for their help during sampling.

Sampling

From the wealth of documentary sources available it was believed that the Keep was built in the early years of the seventeenth century, being particularly the work of Sir Charles Cavendish. Construction was completed by his son, William, building work being finished, it is thought, by AD 1621 at the latest. Sampling and analysis by tree-ring dating of the timbers in the roof of the Keep, the only area with timbers available, were commissioned by English Heritage to confirm this dating and to help inform the management of the wider castle site in general.

The main covering to the Keep consists of two low, shallow pitched, hipped roof areas to the east and west of a central cupola with a flatter area between them. Beneath the lead covering of each roof are found four trusses consisting of tiebeams and king-posts, with short additional posts, supporting principal rafters. An illustration of a truss is given in Figure 4. Hip rafters are to be found at the north and south ends of each roof. Between the trusses run substantial longitudinal battens supporting the boarded roof and lead covering. The ceiling to the room below the roof consists of principal and common joists.

From these two roof areas a total of sixteen samples, eight from each area, was obtained by coring. Each sample was given the code BLS-B (for Bolsover, site "B") and numbered 01 – 16. The position of these samples are shown on drawings made and provided by Richard Sheppard, reproduced here as Figure 5a-d. Details of the samples are given in Table 1. In this report the roofs are described as being either the east or west roof, with the beams and other timbers being numbered and described on a north-south, or east-west basis as appropriate. Because of the shallow pitch and hipped nature of the roof while most timbers were visible, not all of them were accessible for coring, particularly towards the eaves and in the area between the two roofs.

Analysis

Each of the sixteen samples was prepared by sanding and polishing and their annual growth-ring widths measured. The data of these measurements are given at the end of the report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see appendix) and, at an unusually high minimum t-value of 6.2, all sixteen samples cross-matched with each other to form a single site chronology, BLSBSQ01, of length 218 rings. A bar diagram showing the relative positions of the samples in this site chronology is given in Figure 6.

Site chronology BLSBSQ01 was then satisfactorily dated against a number of relevant reference chronologies for oak as spanning the period AD 1532 to AD 1749, the t-values for these cross-matches being given in Table 2.

Interpretation

Five of the sixteen samples obtained, two from the east roof and three from the west, retain complete sapwood: that is, they have the last ring that the tree from which they were taken produced before it was felled. In each case the last measured, complete, sapwood ring date is the same, this being AD 1749. The relative position of the heartwood/sapwood boundaries on all the other dated samples is consistent with a group of timbers having a single felling date and these were almost certainly felled in AD 1749 too. There appears to be no structural or stylistic evidence that any of the timbers found in the two roof spaces are of different dates.

Conclusion

Sampling and analysis by tree-ring dating has produced a single site chronology, BLSBSQ01, consisting of all sixteen samples, this being 218 rings long and dated as spanning the years AD 1532 - AD 1749. Interpretation of the sapwood and the heartwood/sapwood boundaries on the samples would suggest that all the timber used, in both parts of the roof, was cut in a single felling operation in AD 1749.

Such a date is considerably removed from that of AD 1621, the latest date previously expected for this roof, this dating being in the belief that it was contemporary with the primary construction of the building beneath. Analysis has shown that the present roof is much later than the building and again illustrates the value of undertaking tree-ring analysis even in buildings as firmly dated as this is. Furthermore, the specific date of AD 1749 might be particularly unexpected because it is known from documentary sources (Sheppard 2003) that parts of Bolsover Castle, particularly the Terrace Range, were stripped of materials from AD 1751 to furnish Welbeck Abbey nearby, which had became the principal residence of the estate. It is known from these same sources, however, that some, unspecified, parts of the castle were maintained. In particular there is an entry for AD 1750 stating that "upwards of £500 has been spent on repairs", with many invoices showing expenses for carpentry and the sawing up of timber.

It is perhaps difficult to see a context for the expenditure of such a sum in relation to the roof of the Keep. It is possible that the original early seventeenth-century roof had failed and simply needed replacement at this time. It is also possible that the damage caused by the Civil War had been more extensive than hitherto believed (is it known that battlements of the Little Castle were pulled down), and had gone unrepaired for a century. Previous tree-ring analysis at Bolsover has shown that some timbers used in the Riding School were also felled some time in the mid-eighteenth century and again indicate that some maintenance and repair was being undertaken.

In this context it may be noticed from the t-values of Table 2 that the material from the roof of the Keep and that from the Riding House cross-match with each other with an extremely high and unusual value of t=20.1. Such a value would indicate that the trees used for the Keep and those of this date from the Riding School site chronology (the corbels of the riding arena) must have come from the same patch of woodland and have been growing virtually next to each other.

This similarity of source for the two sets of timbers may be seen in the high number of rings found in the samples from both areas. It will be seen from Table 1 again that all the samples from the roof of the Keep have 100+ rings, some of them having well over this, and one, sample BLS-B09, having over 200 rings. High ring numbers are also a feature of the samples from the corbels of the riding school.

The source of both these sets of timbers, those for the Riding School and the roof of the Keep are of course unknown at the moment. It is likely, however, that they are from the Welbeck estate, and it is possible that a search of the documentary sources might prove this.

Being long-lived, the material from Bolsover has provided useful data for a post medieval site chronology for this part of Derbyshire and the East Midlands. Such a site chronology is likely to be very helpful in the dating of other late buildings.

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Table 1: Details of samples from the roof of the Keep or "Little Castle", Bolsover Castle

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	West roof					
BLS-B01	West principal rafter, truss 1	176	h/s	AD 1553	AD 1728	AD 1728
BLS-B02	Tiebeam, truss 1	172	h/s	AD 1540	AD 1711	AD 1711
BLS-B03	West principal rafter, truss 2	181	28C	AD 1569	AD 1721	AD 1749
BLS-B04	West rafter no 1, truss 2 – 3	104	6	AD 1606	AD 1703	AD 1709
BLS-B05	East principal rafter, truss 3	163	h/s	AD 1554	AD 1716	AD 1716
BLS-B06	East rafter no 1, truss 3 – 4	127	53C	AD 1623	AD 1696	AD 1749
BLS-B07	East ceiling joist no 1, truss 3 – 4	100	no h/s-	AD 1587	------	AD 1686
BLS-B08	South-west diagonal ceiling joist	174	h/s	AD 1536	AD 1709	AD 1709
	East roof					
BLS-B09	Tiebeam, truss 3	208	27C	AD 1542	AD 1722	AD 1749
BLS-B10	East principal rafter, truss 3	191	h/s	AD 1532	AD 1722	AD 1722
BLS-B11	East principal rafter, truss 4	185	h/s	AD 1540	AD 1724	AD 1724
BLS-B12	North central trimmer joist	161	h/s	AD 1570	AD 1730	AD 1730
BLS-B13	Tiebeam, truss 1	140	29C	AD 1610	AD 1720	AD 1749
BLS-B14	West principal rafter, truss 1	170	h/s	AD 1553	AD 1722	AD 1722
BLS-B15	East principal rafter, truss 2	144	23C	AD 1606	AD 1726	AD 1749
BLS-B16	East central ceiling joist, truss 2 – 3	123	h/s	AD 1600	AD 1722	AD 1722

h/s = heartwood/sapwood boundary is last ring on
C = complete sapwood retained on sample

Table 2: Results of the cross-matching of site chronology BLSBSQ01 and relevant reference chronologies when first ring date is AD 1532 and last ring date is AD 1749

Reference chronology	Span of chronology	*t*-value	
Bolsover Castle, Derby (Riding house)	AD 1494 – 1744	20.1	(Howard *et al* forthcoming)
East Midlands	AD 882 – 1981	11.2	(Laxton and Litton 1988)
Brewhouse Yard, Nottm	AD 1544 – 1701	10.5	(Howard *et al* 1994)
England	AD 401 – 1981	8.9	(Baillie and Pilcher 1982 unpubl)
Rufford Mill, Notts	AD 1571 – 1744	8.4	(Laxton and Litton 1988)
Sinai Park, Staffs	AD 1227 – 1750	8.2	(Tyers 1997)
Bretby Hall, Bretby, Derbys	AD 1494 – 1718	8.2	(Howard *et al* 1999)
Home Farm, Formark, Derbys	AD 1605 – 1752	7.3	(Howard *et al* 1992)
England London	AD 413 – 1728	6.2	(Tyers and Groves 1999 unpubl)

Figure 1: Map to show general location of Bolsover Castle

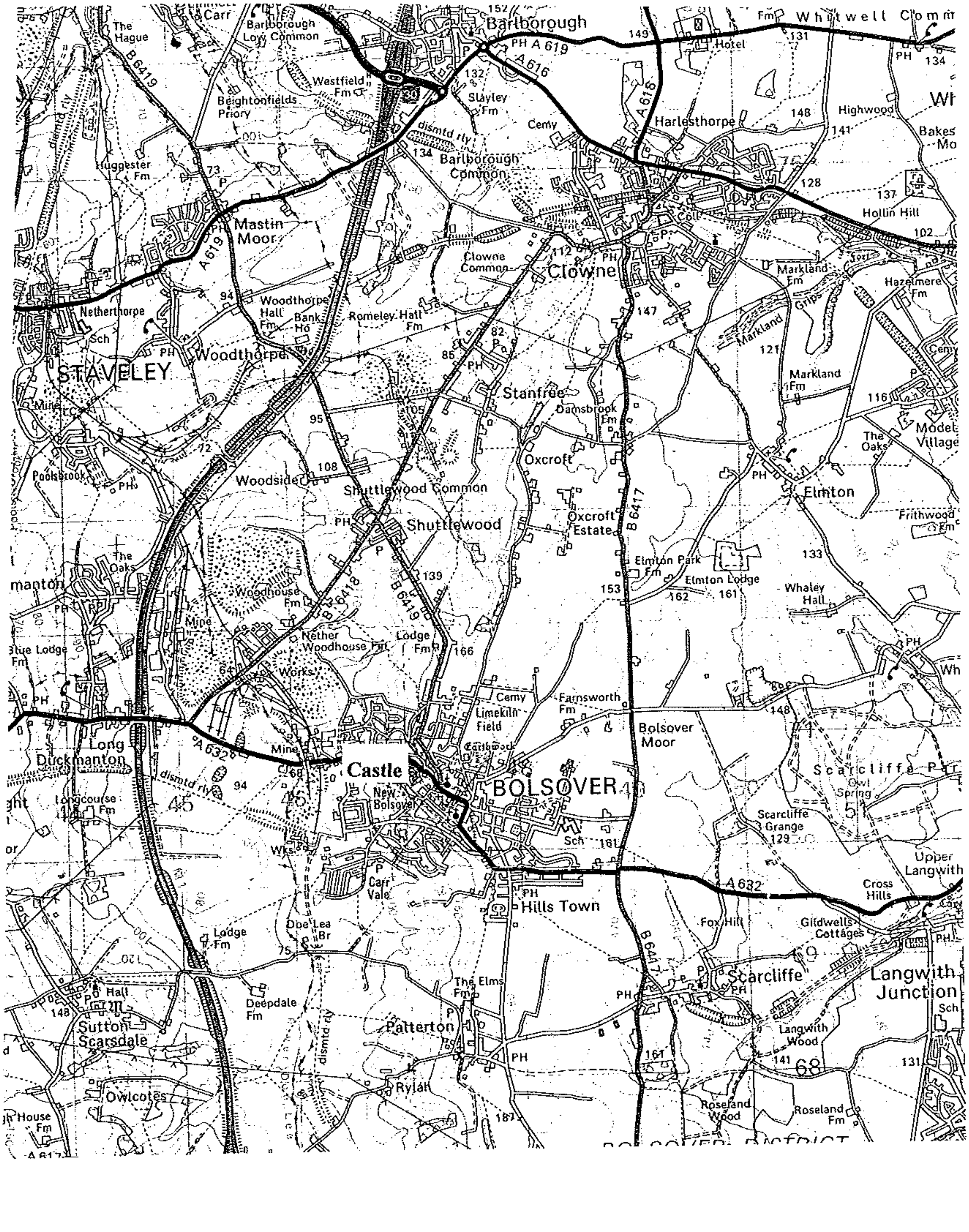


Figure 2: Map to show specific location of Bolsover Castle

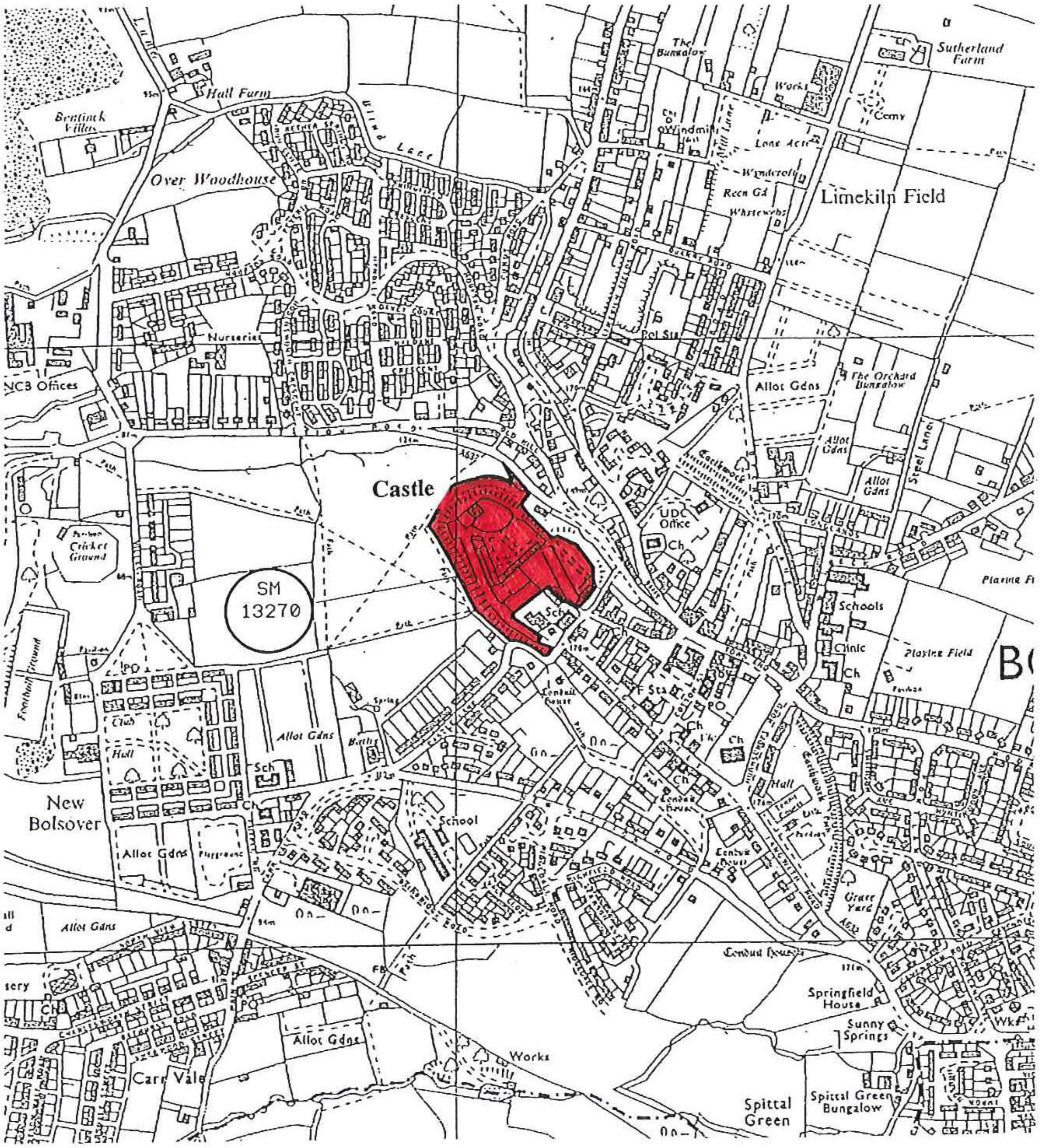


Figure 3

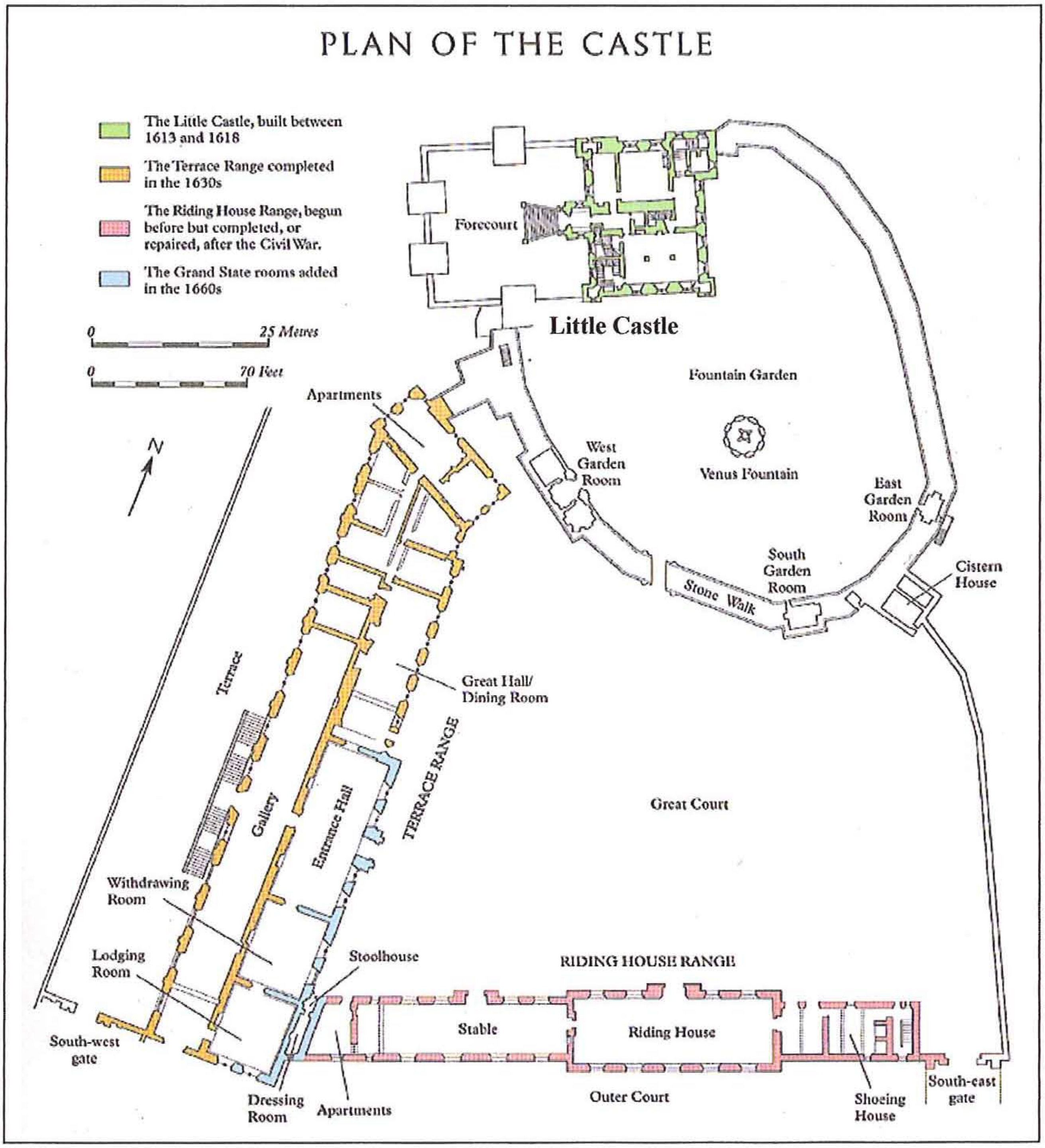

PLAN OF THE CASTLE
The Little Castle, built between 1613 and 1618
The Terrace Range completed in the 1630s
The Riding House Range, begun before but completed, or repaired, after the Civil War.
The Grand State rooms added in the 1660s
0
25 Metres
0
70 Feet
N
Forecourt
Little Castle
Fountain Garden
Venus Fountain
West Garden Room
East Garden Room
South Garden Room
Stone Walk
Cistern House
Apartments
Terrace
Great Hall/ Dining Room
TERRACE RANGE
Gallery
Entrance Hall
Great Court
Withdrawing Room
Lodging Room
Stoolhouse
RIDING HOUSE RANGE
Stable
Riding House
South-west gate
Dressing Room
Apartments
Outer Court
Shoeing House
South-east gate

Figure 4: Illustrative example of a typical truss (viewed from the south)

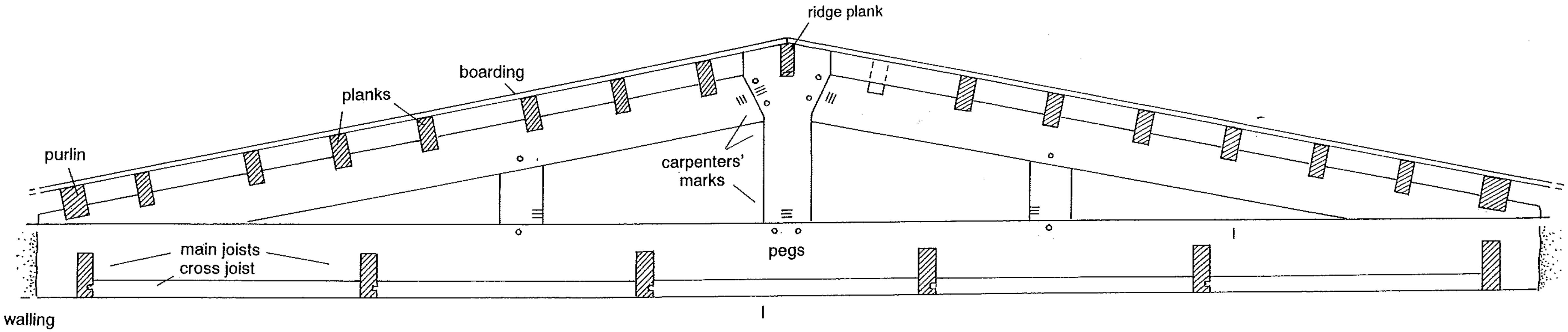


Figure 5a: Bolsover Castle, west roof of Little Castle; plan of rafters to show position of timbers sampled

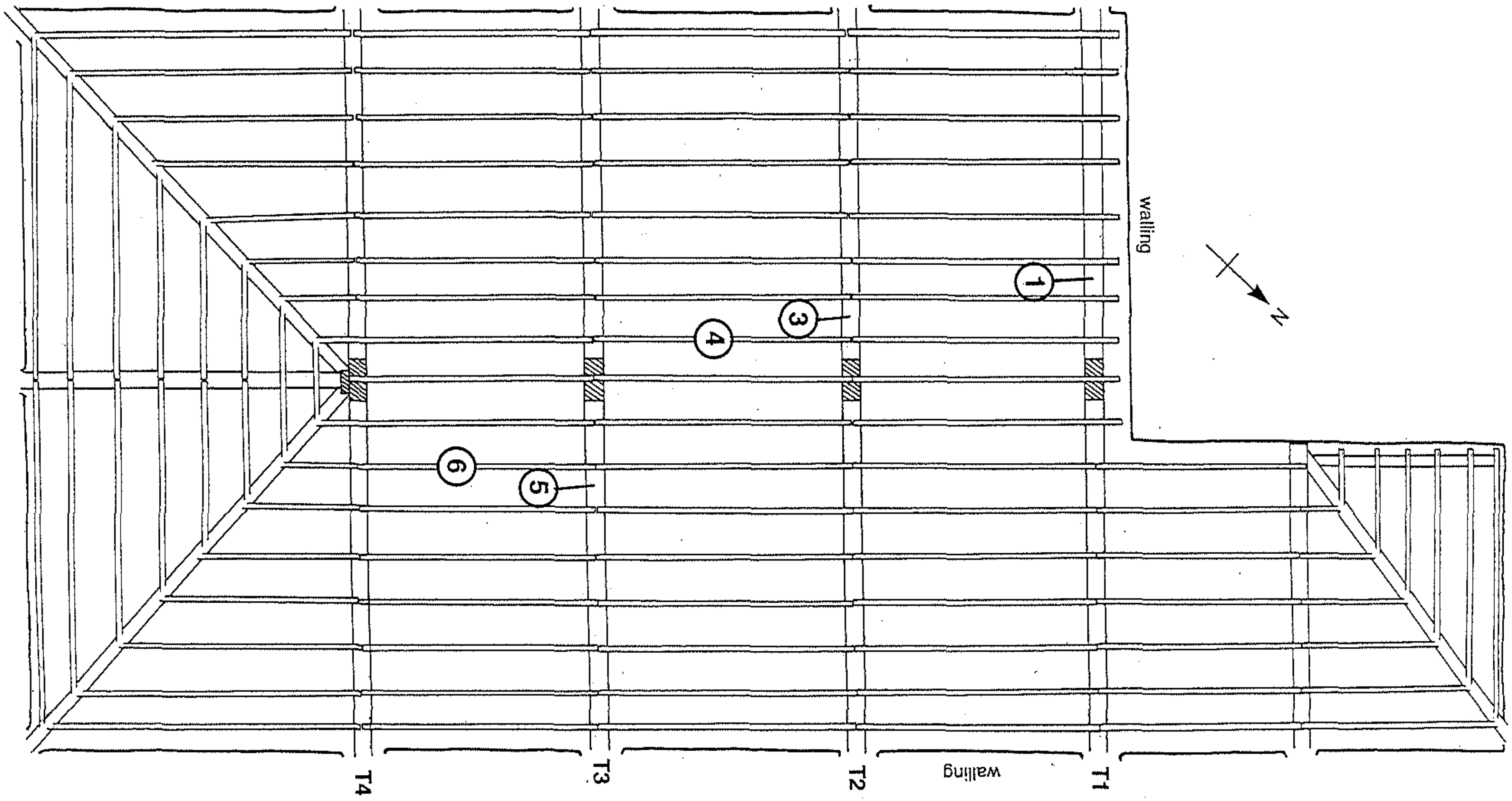


Figure 5b: Bolsover Castle, west roof of Little Castle; plan of tiebeams and joists to show position of timbers sampled

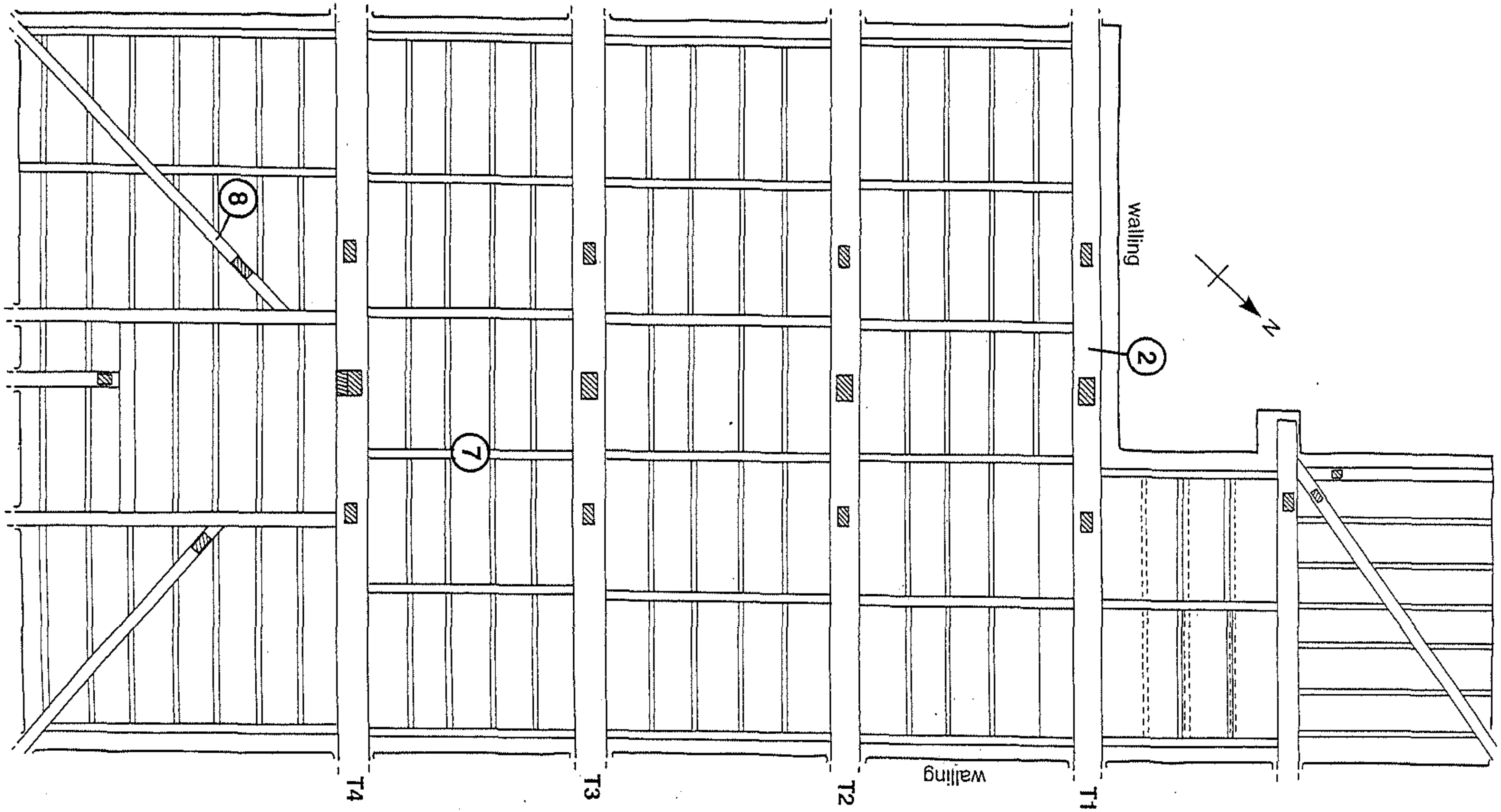


Figure 5c: Bolsover Castle, east roof of Little Castle; plan of rafters to show position of timbers sampled

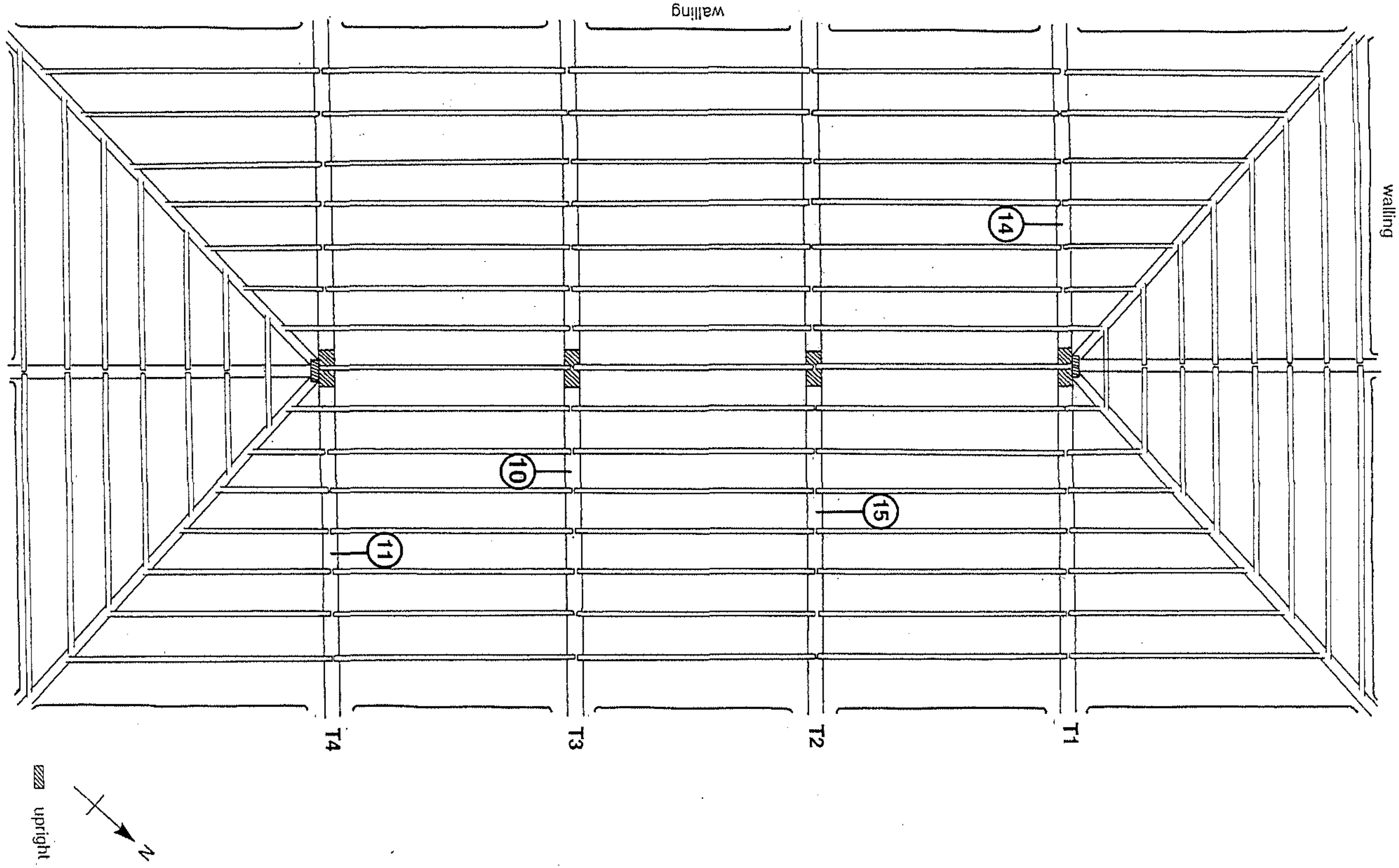


Figure 5d: Bolsover Castle, east roof of Little Castle; plan of tiebeams and joists to show position of timbers sampled

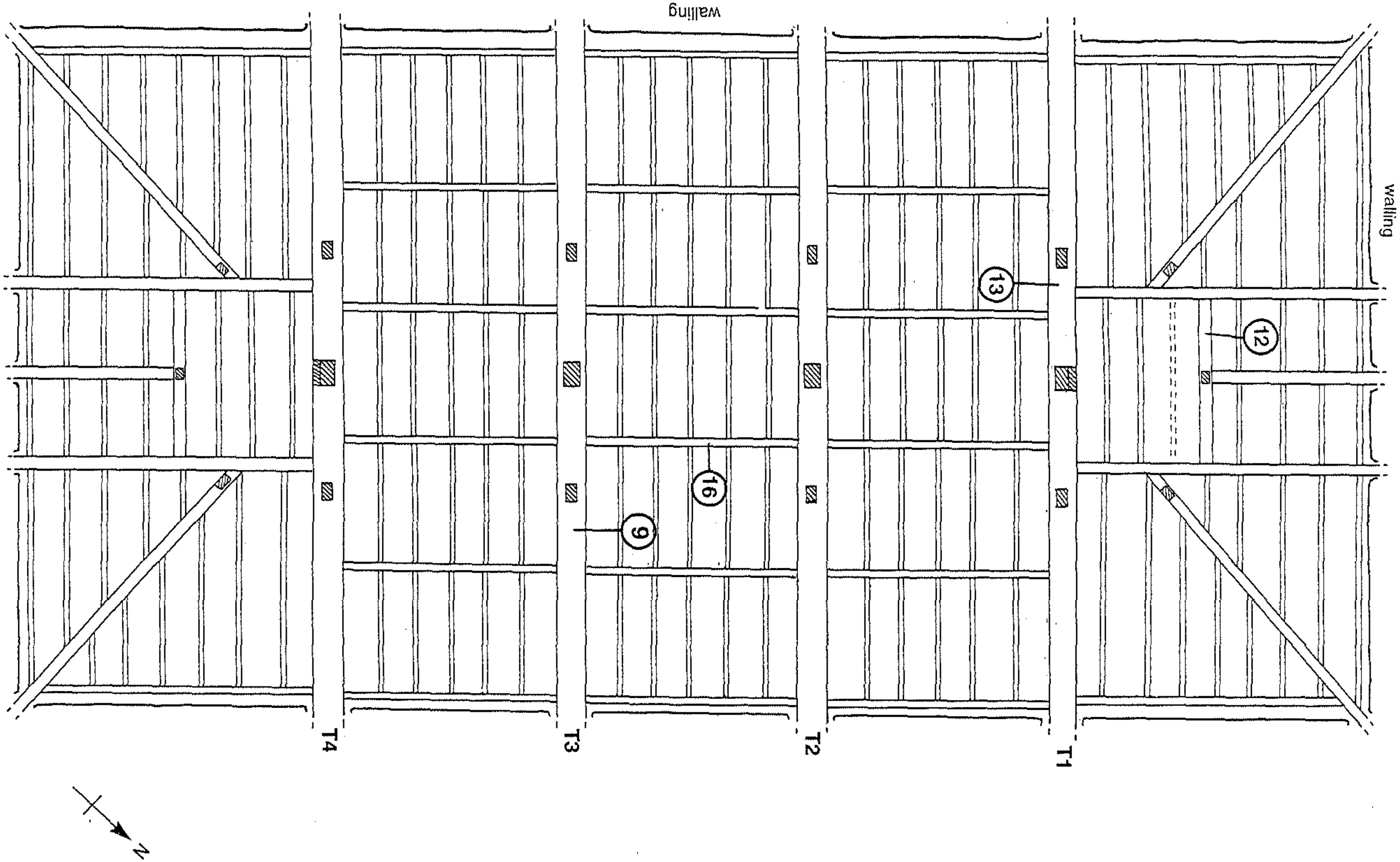
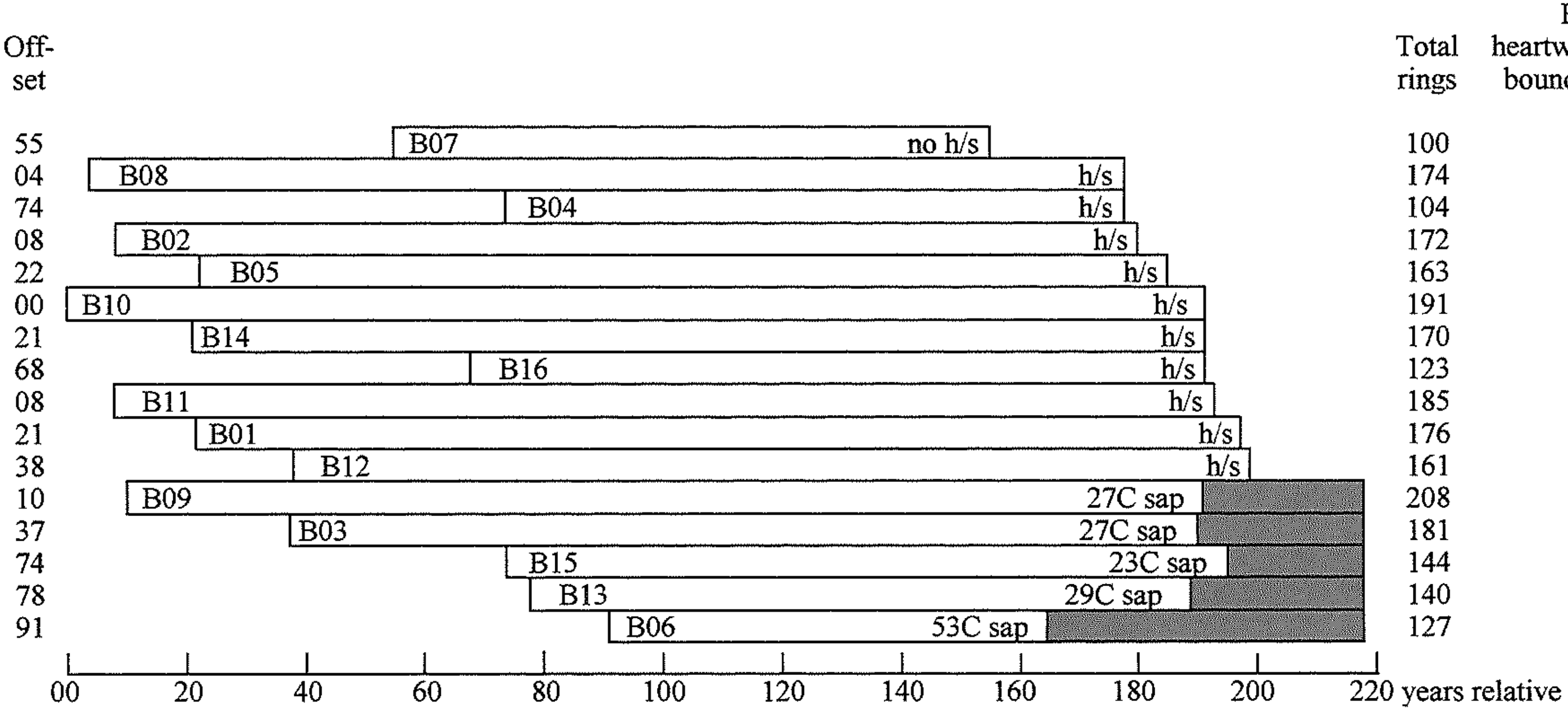


Figure 6: Bar diagrams of the samples in site chronology BLSBSQ01



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

Data of measured samples – measurements in 0.01 mm units

BLS-B01A 176
259 260 269 204 107 158 244 210 271 240 249 187 115 76 128 178 158 169 175 191
125 136 114 96 77 94 178 194 129 139 193 199 177 196 118 114 108 131 95 103
111 142 173 120 141 150 63 73 66 58 62 73 70 77 68 72 38 45 47 49
50 50 43 43 47 42 53 73 96 106 74 62 51 42 60 89 73 42 52 65
53 39 55 39 66 65 50 67 47 51 40 59 62 175 131 111 124 87 66 63
72 81 136 182 123 159 127 126 82 64 69 40 59 48 49 70 99 94 102 79
45 55 41 55 74 61 76 58 52 48 29 36 29 34 23 35 33 21 21 23
23 21 29 23 26 38 30 38 45 39 44 64 46 49 61 62 59 42 38 48
53 52 96 79 100 79 81 67 61 93 80 126 102 103 110 99
BLS-B01B 176
247 268 268 217 110 155 244 210 275 239 265 190 132 76 143 179 158 148 182 193
179 180 112 93 79 100 173 200 161 136 208 208 152 171 111 119 117 127 93 103
97 152 175 123 153 135 67 74 61 69 65 76 69 80 63 68 44 36 55 53
43 51 47 41 49 45 50 72 101 106 81 63 64 49 66 74 78 44 54 60
50 44 48 45 61 72 48 67 49 49 40 57 72 165 137 104 122 86 70 58
78 95 131 171 128 154 129 151 75 63 58 42 54 47 56 68 95 91 106 84
44 52 49 43 79 61 73 65 48 50 36 30 34 32 28 34 27 25 31 10
21 25 27 23 42 36 36 37 48 38 41 60 49 58 48 73 60 45 34 52
53 49 93 79 101 77 86 64 60 92 87 113 98 108 105 97
BLS-B02A 172
276 371 224 325 411 436 368 295 326 294 358 356 252 302 256 373 218 119 127 228
166 160 115 125 152 121 143 178 210 168 184 178 177 201 151 139 94 87 74 142
168 121 92 154 159 169 159 99 81 122 80 79 118 112 121 141 118 87 86 76
53 67 74 118 107 90 97 83 84 76 93 62 69 70 46 39 37 57 74 56
55 64 71 42 30 31 27 35 52 67 32 34 69 49 27 40 38 50 47 46
42 39 22 32 29 29 31 36 36 27 25 29 23 24 24 37 33 33 43 52
40 25 30 42 43 36 22 31 35 46 33 44 34 27 46 52 44 67 75 60
49 43 39 46 43 43 48 49 48 58 31 38 26 32 31 23 30 43 42 30
22 33 37 33 31 26 18 30 34 44 38 49
BLS-B02B 172
277 364 246 338 418 440 388 283 402 357 354 348 249 299 275 344 273 111 129 231
164 158 118 123 140 130 148 182 202 165 178 201 181 196 156 139 94 88 76 144
167 121 98 147 168 173 152 93 101 120 79 90 113 111 129 136 118 96 94 63
61 62 74 116 104 98 84 88 84 80 83 60 70 72 45 36 40 52 77 59
51 63 73 44 30 27 30 39 52 63 28 36 66 48 26 39 42 45 52 45
22 43 27 29 24 33 29 35 34 24 21 35 23 22 28 32 30 32 48 50
36 27 26 50 28 49 20 30 36 46 32 41 31 34 48 47 44 72 69 69
57 36 52 43 38 44 49 49 39 65 33 29 25 30 35 31 31 45 46 32
31 24 31 32 30 30 25 29 28 48 44 57
BLS-B03A 181
126 202 168 160 182 176 169 134 118 153 148 119 118 104 128 120 124 152 96 69
89 80 60 59 54 67 96 100 73 63 47 55 52 63 87 96 90 118 95 96
62 92 123 131 120 98 55 77 110 144 130 140 137 155 111 87 113 102 154 170
160 145 146 178 140 96 85 83 130 149 120 166 170 85 114 151 165 169 144 180
110 92 62 70 66 84 120 134 114 129 95 113 98 104 108 89 91 106 105 123
123 110 112 108 46 70 111 89 112 117 84 121 114 104 78 58 88 109 113 112

130 103 70 58 91 153 118 125 112 106 110 108 95 97 113 110 91 88 99 109
95 44 81 99 102 82 76 115 117 114 82 59 89 110 83 118 106 101 120 112
114 127 126 105 116 132 91 67 62 59 79 99 112 98 85 85 110 138 97 82
96
BLS-B03B 181
130 197 175 153 190 171 171 133 128 139 149 122 116 98 128 118 124 152 90 79
85 79 60 60 57 71 96 75 66 68 56 55 44 63 88 88 96 115 102 89
59 98 121 124 137 96 56 66 111 144 127 133 133 157 119 89 105 109 161 155
172 142 151 181 137 95 86 88 139 145 126 158 176 97 109 149 165 168 144 163
105 88 69 68 62 83 124 126 118 122 103 107 103 101 103 91 96 102 105 122
124 119 106 108 48 76 103 85 120 116 93 117 112 105 76 59 90 110 111 111
129 101 71 59 93 151 112 124 116 113 111 101 98 103 109 112 82 74 94 114
87 56 79 101 95 77 84 110 124 97 68 74 73 109 87 117 111 105 120 107
108 120 122 110 129 123 95 64 68 49 88 92 106 89 91 82 112 130 107 82
116
BLS-B04A 104
237 186 150 140 207 193 249 232 130 137 154 179 233 173 196 202 249 144 119 126
103 142 213 222 158 186 182 160 92 93 71 94 95 81 136 133 89 94 99 91
120 113 87 88 67 67 56 55 47 120 150 138 139 103 99 85 95 79 55 77
67 72 93 118 124 106 89 66 65 58 46 105 131 102 97 95 77 71 53 57
100 89 91 114 60 68 64 86 76 81 87 102 106 73 65 90 59 94 88 60
59 65 82 81
BLS-B04B 104
268 185 154 147 199 194 252 208 120 132 148 177 231 178 199 200 251 143 130 124
105 131 232 237 157 166 183 178 93 93 67 99 94 80 140 125 94 93 98 96
116 108 93 85 74 60 58 56 51 108 162 134 141 107 97 87 84 86 64 76
63 71 94 119 126 97 92 75 58 69 55 86 137 96 105 95 76 59 54 75
90 101 82 109 75 70 66 78 75 87 87 100 91 81 69 91 59 81 82 63
52 68 84 93
BLS-B05A 163
145 219 171 98 172 220 190 217 193 196 134 97 93 137 173 143 166 157 151 147
145 121 77 64 89 145 135 134 104 155 159 142 167 108 108 136 112 118 147 152
168 182 126 152 131 59 79 57 82 104 98 103 111 67 77 76 85 98 104 84
79 63 56 58 113 122 122 150 126 105 58 51 48 78 82 66 44 52 63 61
36 47 42 65 88 56 54 55 39 44 47 50 102 88 69 70 57 34 46 59
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45 43 59 91 82 73 63 48 45 40 46 57 80 89 82 67 58 55 45 39
43 56 57 80 68 46 54 58 59 53 57 59 51 57 53 45 33 30 38 48
47 49 58
BLS-B05B 163
134 199 157 107 165 226 186 223 193 191 136 95 90 153 173 150 171 147 160 150
156 119 74 71 81 153 146 128 104 151 168 132 173 106 112 139 117 110 144 152
166 184 138 131 112 67 80 55 82 101 101 98 108 77 68 56 104 97 124 98
75 54 49 76 99 122 128 137 136 96 46 54 49 82 85 59 46 56 62 55
43 46 43 64 87 57 44 53 45 45 53 46 97 92 73 63 52 43 41 54
56 76 69 45 80 63 53 45 53 52 32 49 44 73 66 94 81 81 69 54
56 45 57 83 79 71 68 40 41 48 43 57 75 101 74 71 55 47 44 41
45 59 57 83 76 54 49 58 53 56 59 55 53 54 48 49 31 34 31 47
52 42 57

BLS-B06A 87
223 213 166 178 202 225 293 160 174 228 192 115 95 87 112 107 88 114 128 84
92 89 96 116 128 117 110 93 78 62 63 62 122 149 141 150 108 97 85 76
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89 67 86 120 136 124 131 71 70 105 87 90 79 79 99 109 67 69 76 54
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BLS-B06B 108
86 102 88 113 99 129 111 111 91 80 63 61 72 140 181 144 149 115 110 89
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57 61 63 43 42 61 65 62 43 45 33 32 29 32 39 44 46 41 32 38
30 28 41 44 39 41 52 58 52 63 66 58 46 42 56 38 56 36 48 52
45 40 44 51 43 36 47 67
BLS-B07A 90
259 335 306 252 210 239 270 312 346 260 272 316 264 225 233 265 300 238 228 240
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178 188 271 198 201 234 190 175 143 217 199 211 124 151 159 73 136 114 166 198
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82 116 94 82 76 65 47 58 48 83
BLS-B07B 100
254 330 307 249 191 237 276 321 330 247 261 322 236 220 218 277 362 248 253 226
196 186 141 167 182 171 215 150 141 118 133 228 212 259 225 228 220 168 143 200
191 188 248 198 214 222 211 176 156 200 203 210 129 147 182 67 124 123 158 207
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90 117 92 86 73 79 34 59 50 76 52 37 38 34 30 32 36 31 35 26
BLS-B08A 174
244 247 287 246 249 172 84 118 101 152 119 120 137 139 207 229 177 190 180 173
128 52 126 175 138 188 172 193 103 66 111 189 144 91 102 98 73 86 117 88
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31 37 36 22 32 31 35 27 48 42 32 49 46 52
BLS-B08B 174
261 256 281 246 255 176 102 128 91 120 118 130 135 144 205 216 184 183 209 166
140 52 127 167 145 182 182 188 115 66 117 181 151 89 101 98 75 83 126 83
79 105 88 109 163 93 99 122 94 92 111 58 89 98 119 75 120 177 137 174
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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 Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring..

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

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

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

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

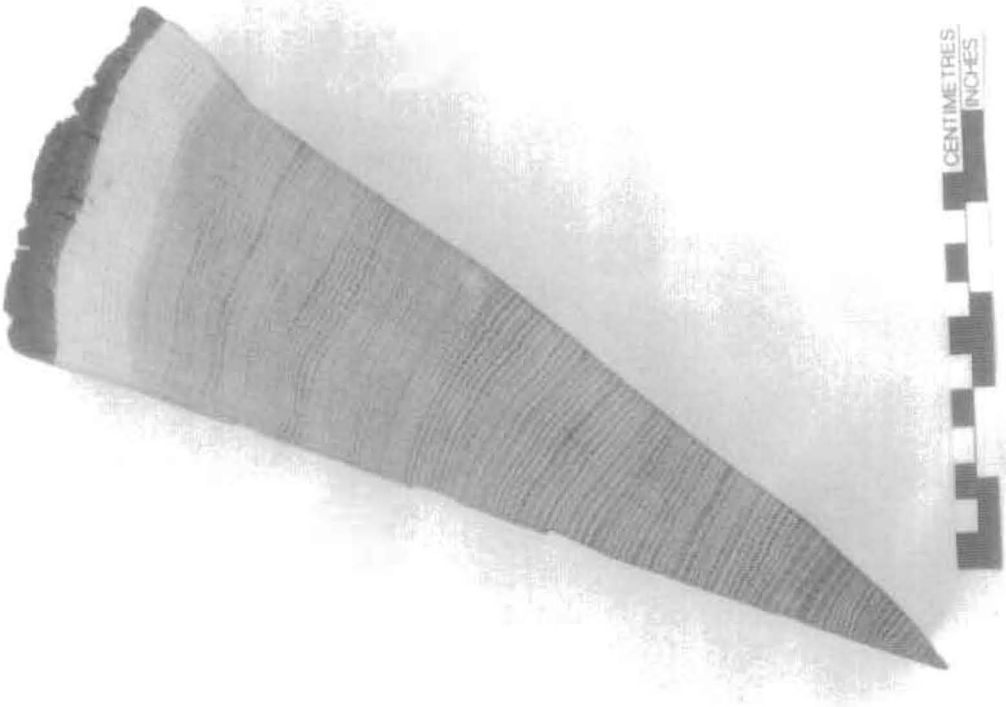


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

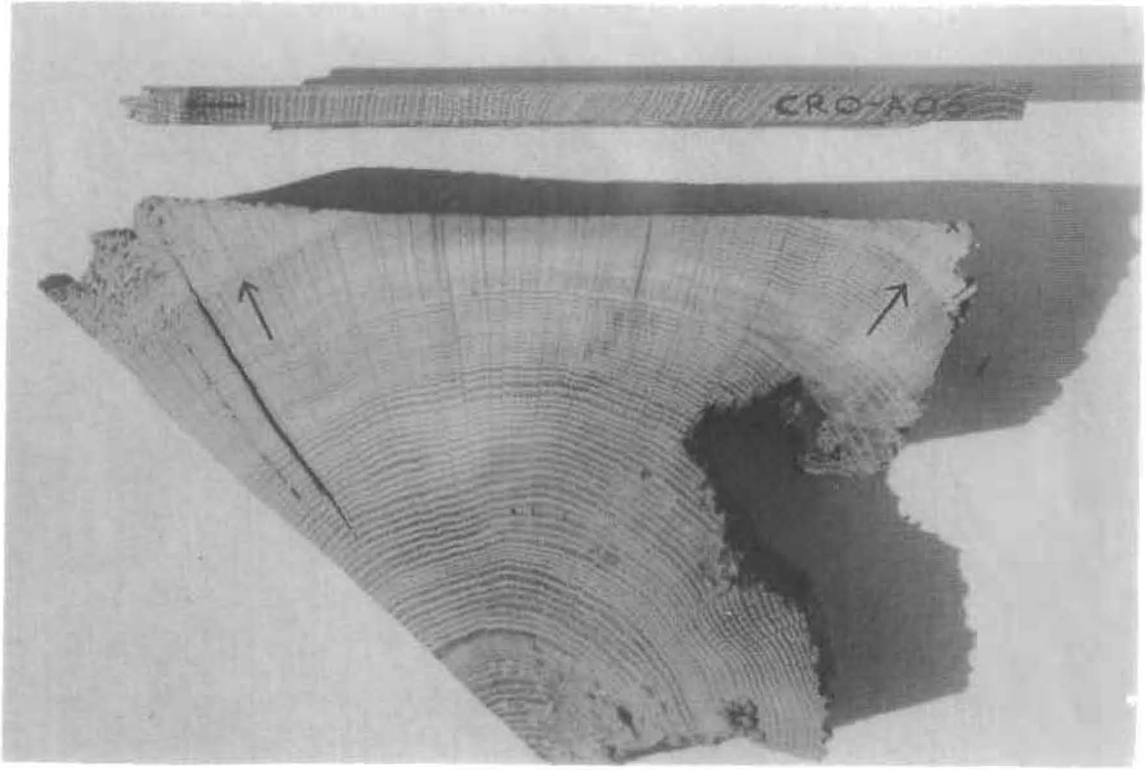


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig 3. Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

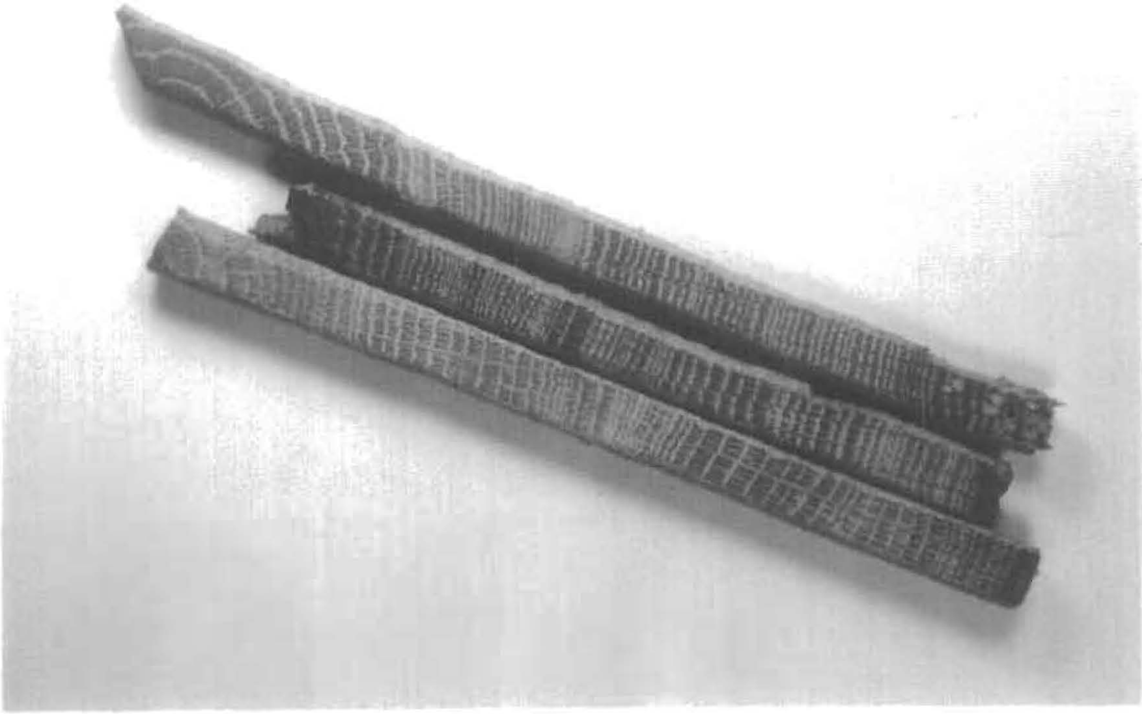


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

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

All sampling by the Laboratory is undertaken according to current Health and Safety Standards.
The Laboratory is insured with the CBA.

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

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

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

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

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

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

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

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

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

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

More precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 40 years later we would have estimated without this observation.

T-value/Offset Matrix

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

Bar Diagram

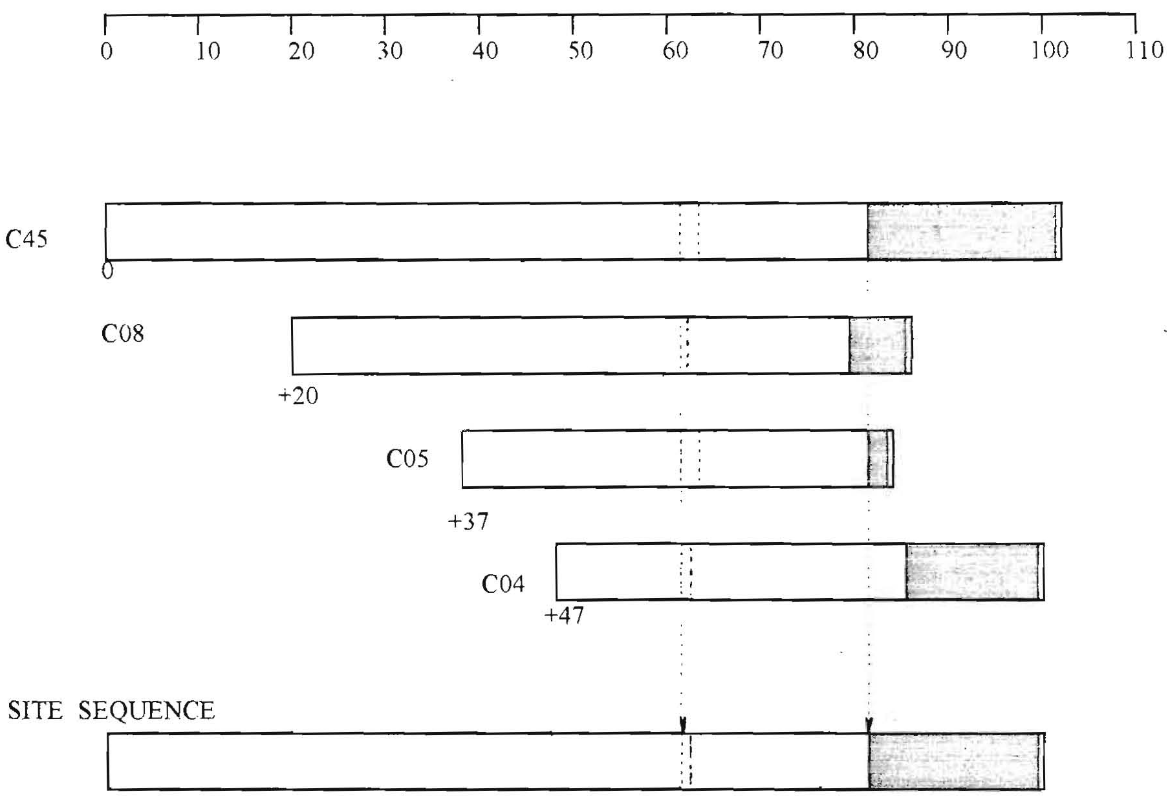


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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

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

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

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

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

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ*, and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed for this.

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

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

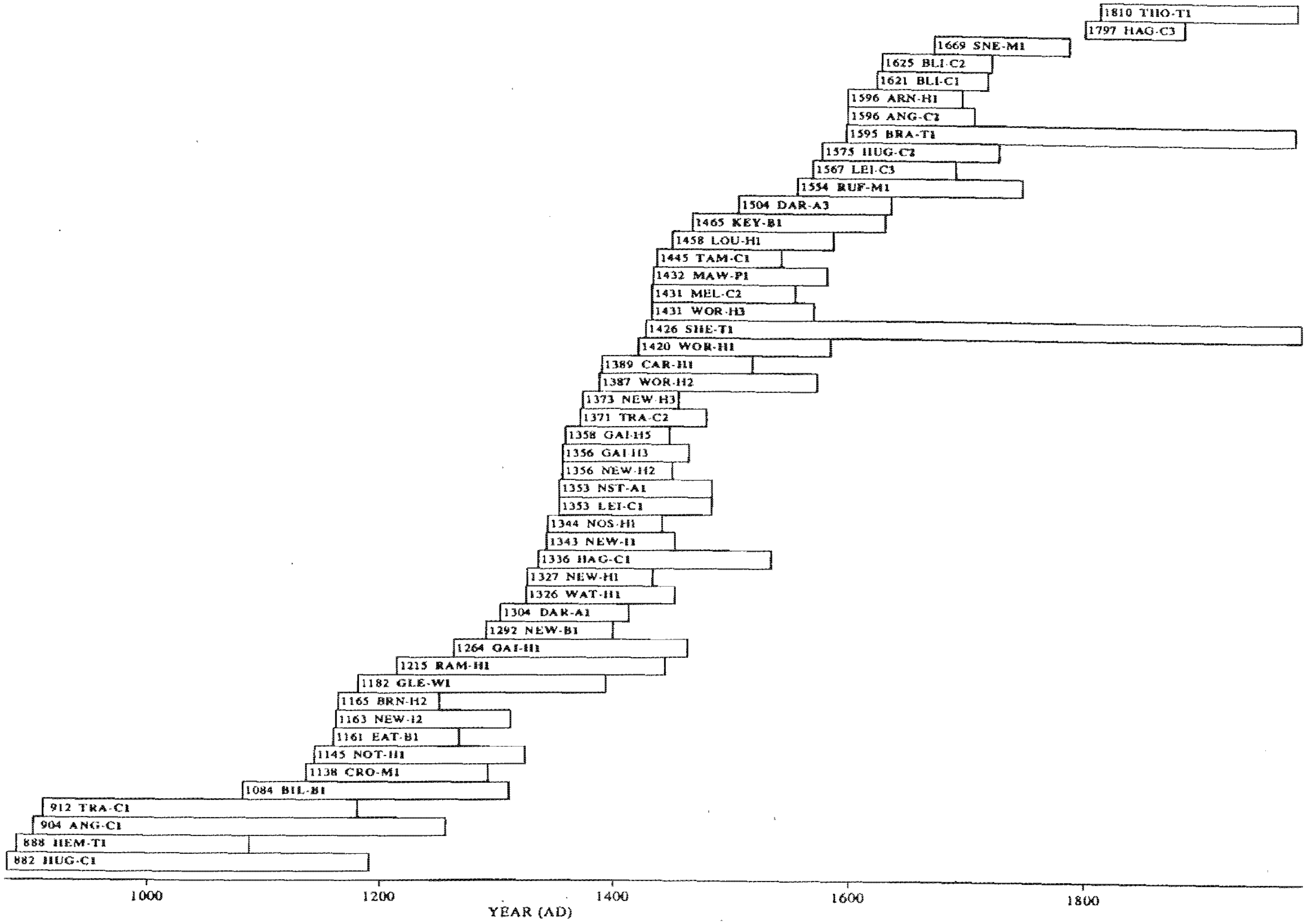
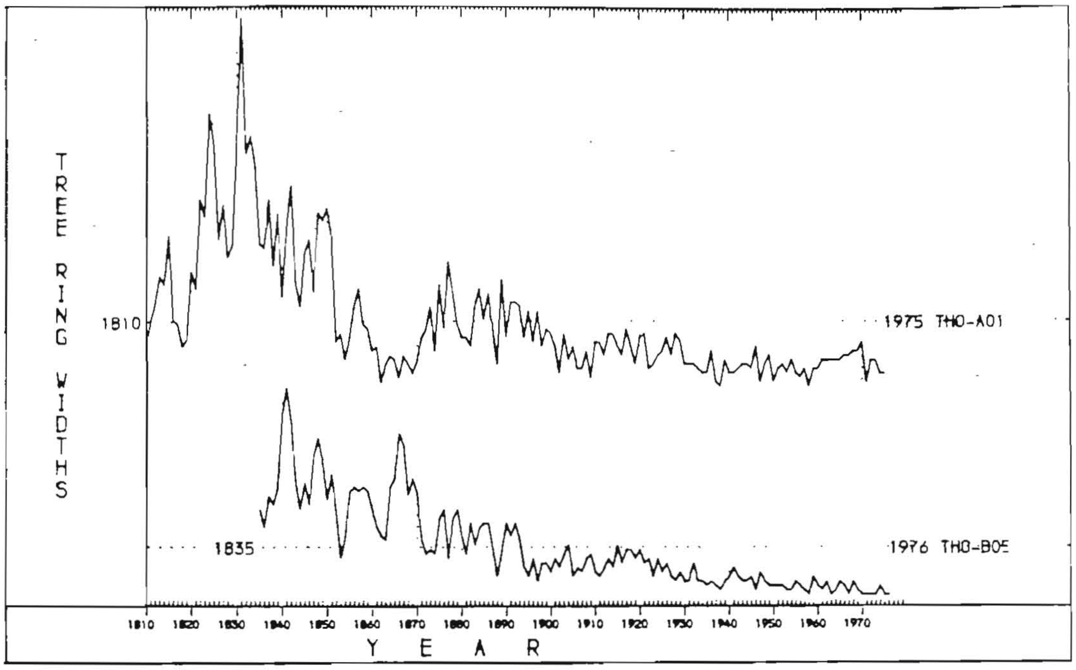


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

(a)



(b)

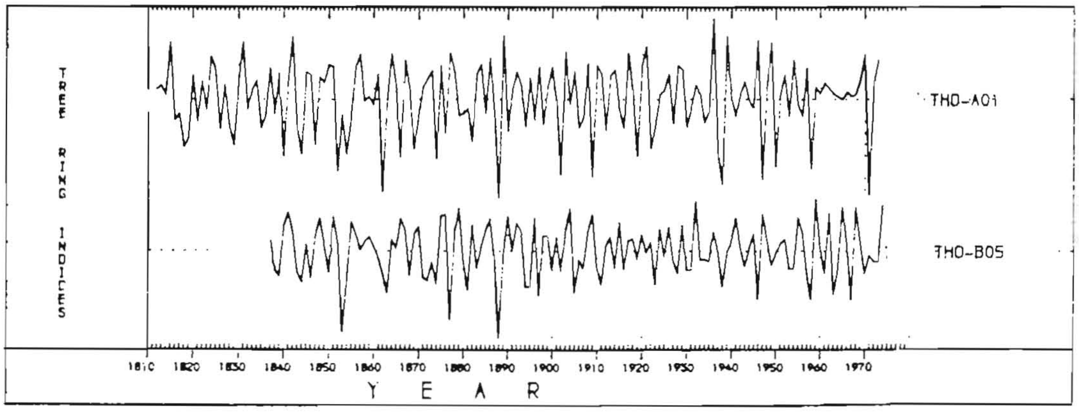


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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