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Tree-Ring Analysis of Timbers from Tunstall Hall Farm, Elwick Road, Hartlepool, Cleveland

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Summary

Fourteen samples from the timbers of the main front-range roof of Tunstall Hall Farm were analysed by tree-ring dating. This analysis produced a single site chronology of 169 rings spanning the period AD 1316 - AD 1484. Interpretation of the sapwood on the samples suggests that all the timbers used in the roof are from trees with a single phase of felling dated to AD 1484.

Keywords

Dendrochronology
Standing Building

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TREE-RING ANALYSIS OF TIMBERS FROM TUNSTALL HALL FARM, ELWICK ROAD, HARTLEPOOL, CLEVELAND

Introduction

Tunstall Hall Farm lies to the west of Hartlepool in the Parish of Tunstall (NZ 493322; Fig 1). It comprises a two-storey hearth-passage farmhouse with an extensive rear extension making it double span, and with a stable wing. All these features disguise the plan and fabric evidence of a possible mid fifteenth- to early sixteenth-century building. Formerly a farmhouse, it is now a private dwelling. It was re-fenestrated in the eighteenth century, and is now rendered and painted. It is currently a grade II listed building.

The primary phase of this high-status house comprises the main three-cell two-storey front range. In the roof of this section is a complete set of eight truncated principal roof trusses of the as yet unpublished Thornes/Hook Classification system type 4B. The date range of type 4B, on stylistic grounds by comparison with many other examples, is generally thought to be in the date range mid-fifteenth to late-sixteenth centuries.

Sampling

Sampling and analysis by tree-ring dating of Tunstall Farm Hall were commissioned by English Heritage. The purpose of this was to establish a date for the roof, to inform a possible listing upgrade and also to inform research into the regional roof construction typology.

The roof is of a fairly simple type consisting of truncated principal rafters with tiebeams and collars, the rafters carrying single purlins. Between the principal rafter trusses are found paired common rafters.

After on-site discussions and in conjunction with the English Heritage brief, a total of fourteen core samples was obtained. Each sample was given the code TUN-A (for Tunstall, site "A"), and numbered 01 – 14. The positions of these samples are marked on plans provided by English Heritage, reproduced here as Figure 2 and Figures 3a-f. Details of the samples are given in Table 1. In this report the bays and trusses have been numbered from west to east with the timbers being identified on a north – south basis as appropriate.

The Laboratory would like to take this opportunity to thank Martin Roberts of the English Heritage North-east Regional Office in Newcastle. Martin Roberts not only helped in accessing the site, but also helped assess the possible phasing of the timbers and provided information used in the introduction above. We would also like to thank the owners of the house, Mr and Mrs Wilson, for their enthusiastic support for this project.

Analysis

Each of the fourteen samples obtained was prepared by sanding and polishing and their annual growth-ring widths measured. The data of these measurements is given at the end of this report. These were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum *t*-value of 4.5 thirteen of them cross-matched with each other, as shown in the bar diagram Figure 4, to form a single site chronology, TUNASQ01, of length 169 rings. Site chronology TUNASQ01 was then compared with a series of relevant reference chronologies for oak, giving it a first ring date of AD 1316 and a last measured ring date of AD 1484. Evidence for the dating of site chronology TUNASQ01 is given in the *t*-values of Table 2.

Four of the samples in the site chronology, TUN-A04, A07, A10, and TUN-A12, all retain complete sapwood, that is, they have the last ring produced by the trees from which they were taken before felling. In all four samples the last measured ring date is the same, AD 1484. The amount of sapwood and the relative position of the heartwood/sapwood boundaries on the other dated samples strongly suggests that all the timbers were cut in a single felling in that year. There is no structural or architectural evidence to suggest that any of these timbers are of a different date.

The single remaining ungrouped sample, TUN-A02, was compared individually with the full range of relevant reference chronologies. Unfortunately there was no cross-matching and this sample must remain undated.

Interpretation and conclusion

Analysis by dendrochronology has produced a single site chronology of 169 rings spanning the period AD 1316 – AD 1484. Given that a sufficient quantity of samples was obtained from a wide range of locations it would appear that the whole roof is of a single phase of construction using trees that were all felled in AD 1484. Such a date would suggest that the example found at Tunstall Hall Farm is towards the earlier end of the range for its roof type in the Thornes/Hook sequence.

A single timber remains undated. There is no apparent reason for this, no sign of any ring problems which might make cross-matching and dating difficult, though the sample is slightly short, having only fifty-five rings.

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Table 1: Details of samples from Tunstall Hall Farm, Hartlepool, Cleveland

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
TUN-A01	South principal rafter, truss 1	97	no h/s	AD 1320	------	AD 1416
TUN-A02	Collar, truss 1	68	18C	------	------	------
TUN-A03	North principal rafter, truss 2	81	no h/s	AD 1346	------	AD 1426
TUN-A04	South common rafter 1, bay 2	54	17C	AD 1431	AD 1467	AD 1484
TUN-A05	South common rafter 2, bay 2	70	11	AD 1396	AD 1454	AD 1465
TUN-A06	South purlin, truss 3 – 4	54	15	AD 1425	AD 1463	AD 1478
TUN-A07	North common rafter 5, bay 3	81	27C	AD 1404	AD 1457	AD 1484
TUN-A08	South common rafter 2, bay 4	93	h/s	AD 1363	AD 1455	AD 1455
TUN-A09	South principal rafter, truss 5	56	2	AD 1413	AD 1466	AD 1468
TUN-A10	South common rafter 2, bay 5	71	19C	AD 1414	AD 1465	AD 1484
TUN-A11	Nurth purlin, truss 5 – 6	83	14	AD 1396	AD 1464	AD 1478
TUN-A12	North principal rafter, truss 6	61	22C	AD 1424	AD 1462	AD 1484
TUN-A13	Collar, truss 6	132	no h/s	AD 1319	------	AD 1450
TUN-A14	Collar, truss 7	128	no h/s	AD 1316	------	AD 1443

*h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood retained on sample, where measured the last ring date is the felling date of the timber

Table 2: Results of the cross-matching of site chronology TUNASQ01 and relevant reference chronologies when first ring date is AD 1316 and last ring date is AD 1484

Reference chronology	Span of chronology	t-value	
Witton Hall, Witton Gilbert, Co Durham	AD 1395 – 1475	11.1	(Howard *et al* 1996)
Kepier Hospital, Durham	AD 1304 – 1522	10.7	(Howard *et al* 1996)
Choir roof, Durham Cathedral	AD 1346 – 1458	10.5	(Howard *et al* 1992)
Seaton Holme, Easington, Co Durham	AD 1375 – 1489	10.4	(Howard *et al* 1988 unpubl)
The Close, Newcastle upon Tyne	AD 1365 – 1513	10.2	(Howard *et al* 1991)
North Transept, Durham Cathedral	AD 1320 – 1457	8.7	(Howard *et al* 1992)
Old Durham Farm, Durham	AD 1390 – 1619	8.1	(Howard *et al* 1995)
East Midlands	AD 882 – 1981	6.3	(Laxton and Litton 1988)
England	AD 401 – 1981	6.1	(Baillie and Pilcher 1982 unpubl)

Figure 1: Map to show general location of Tunstall Farm

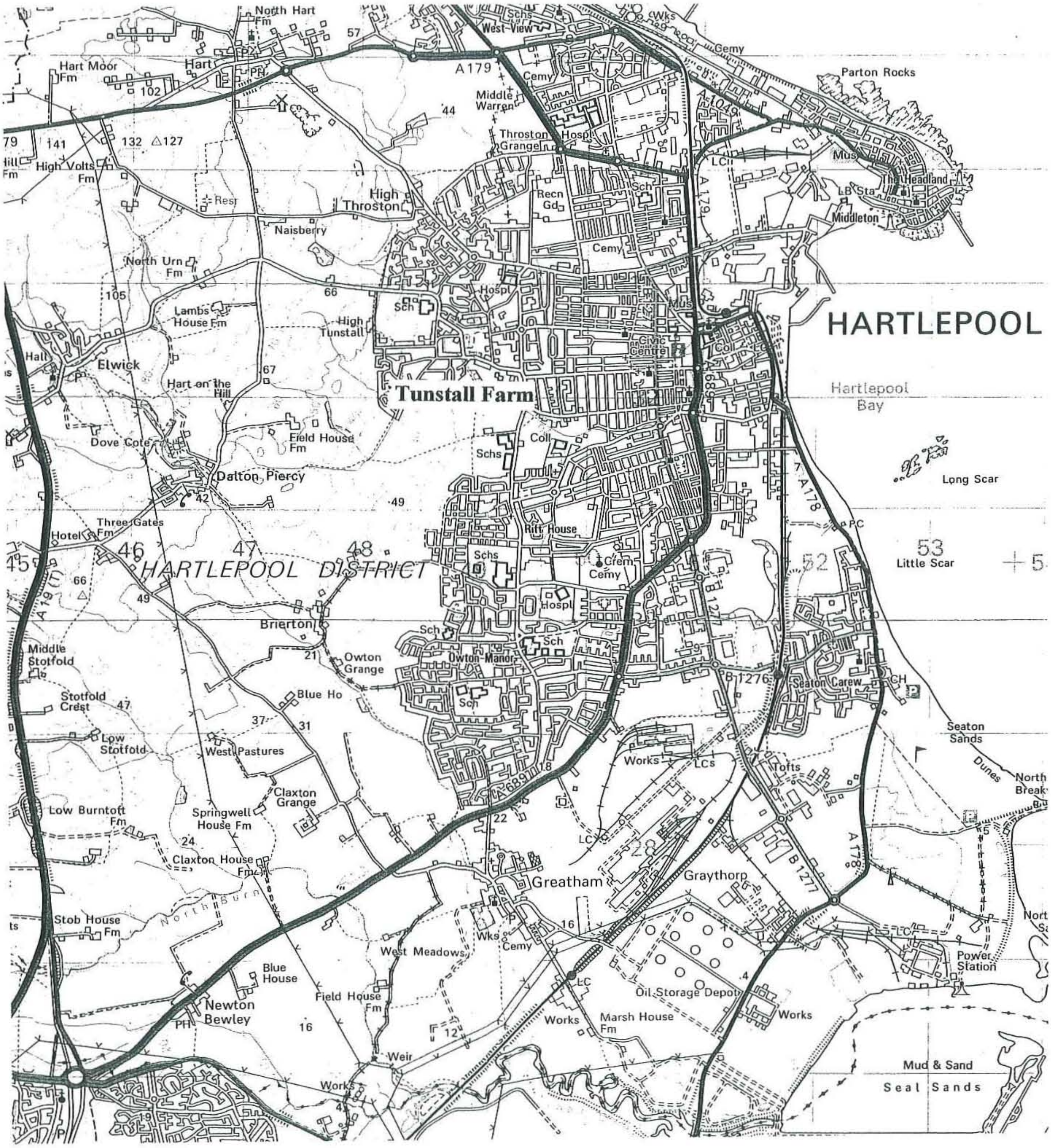


Figure 2: Plan to show location of samples

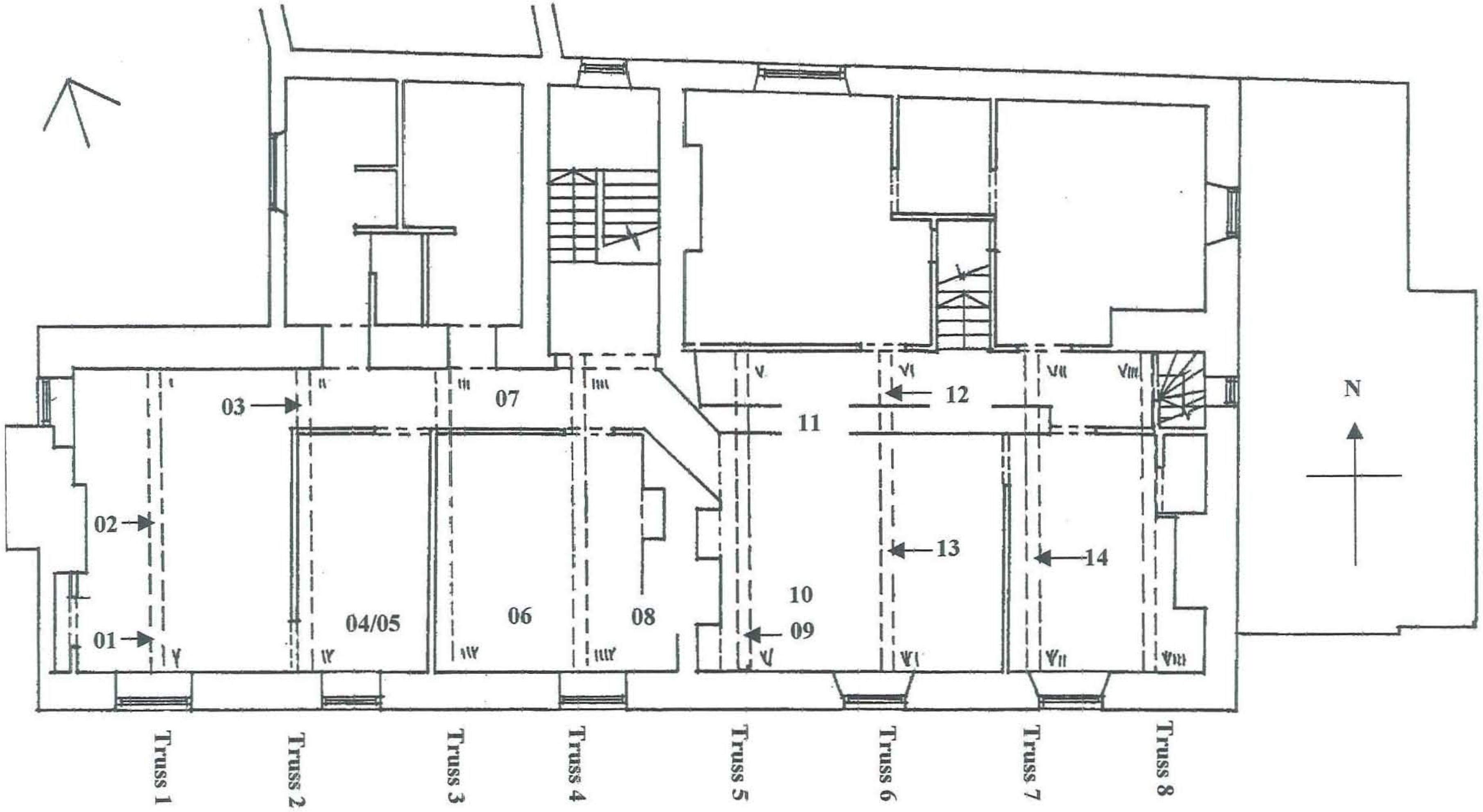


Figure 3a: Drawing to show location of samples from truss 1 (viewed from the east)

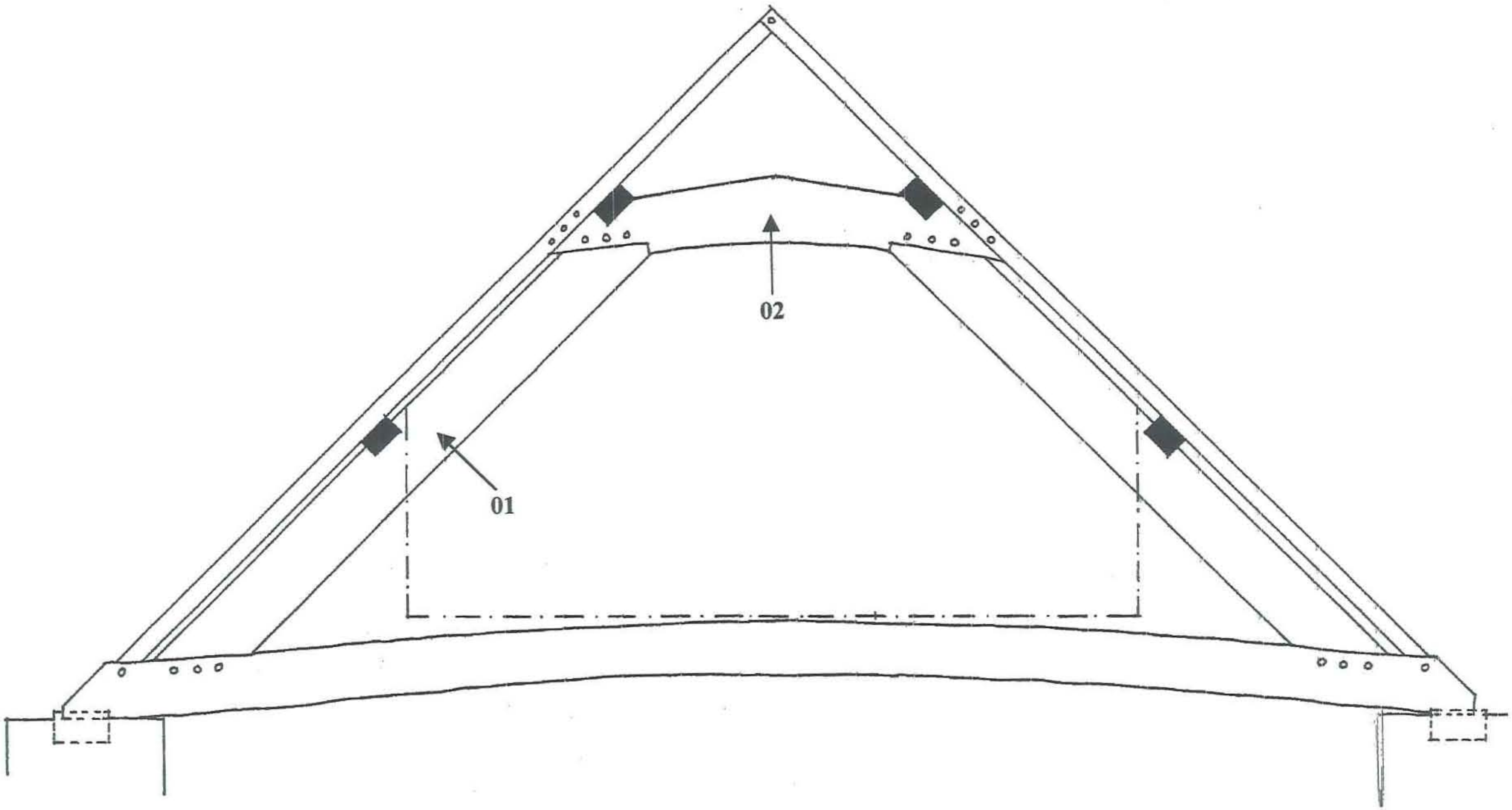


Figure 3b: Drawing to show location of samples from truss 2
(viewed from the east)

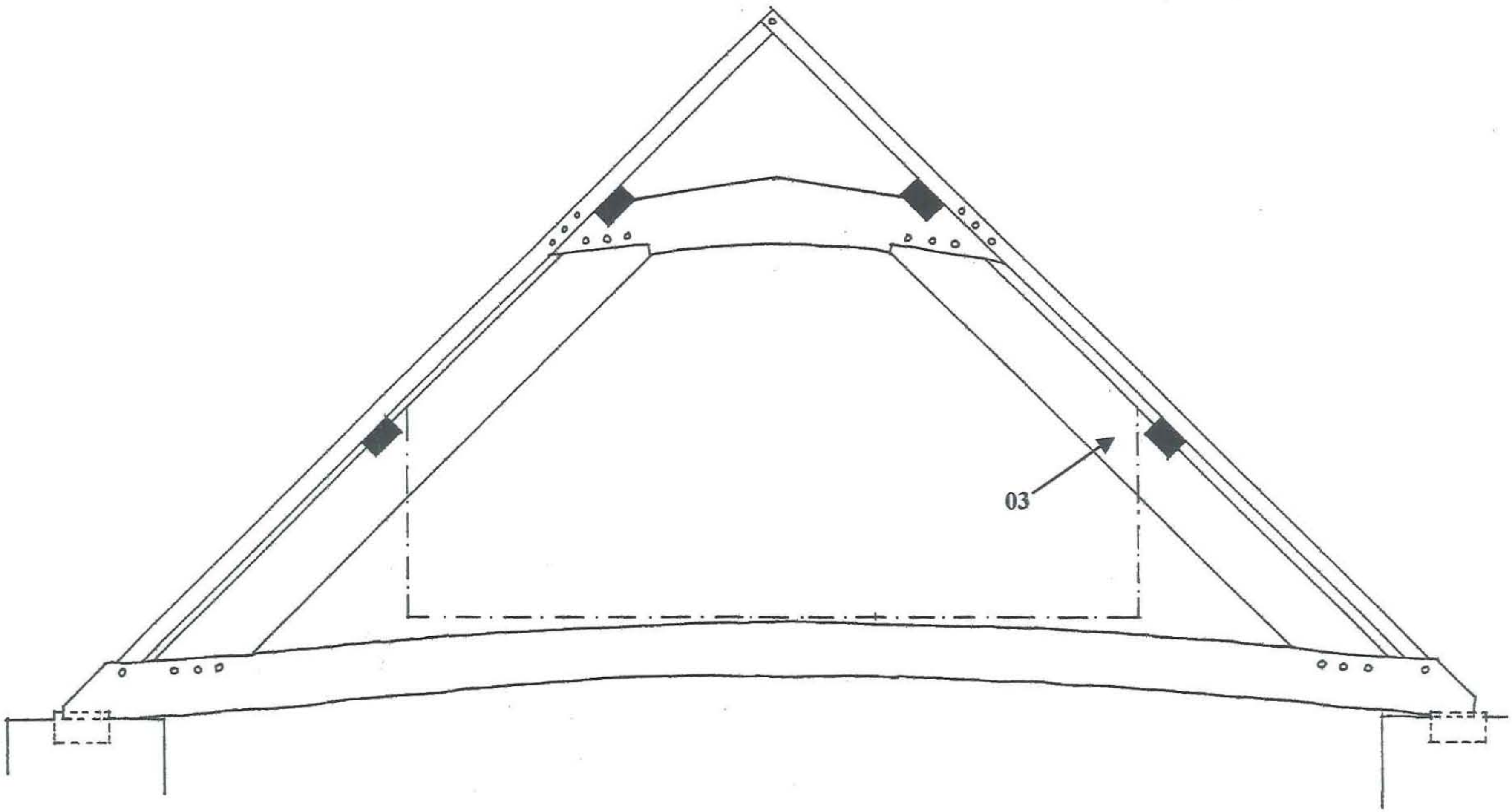


Figure 3c: Drawing to show location of samples from truss 3 - 4 (viewed from the east)

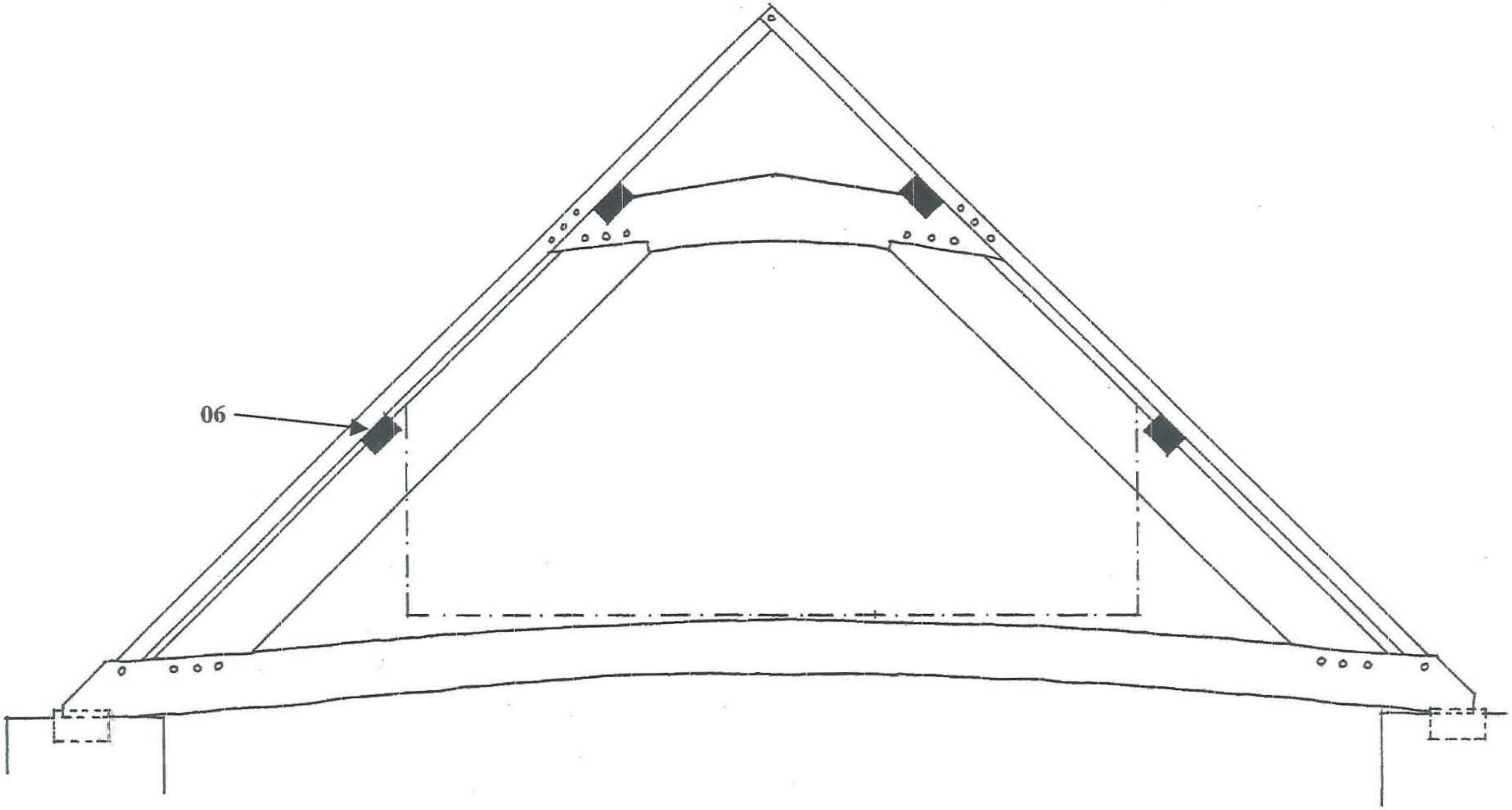


Figure 3d: Drawing to show location of samples from truss 5 (viewed from the east)

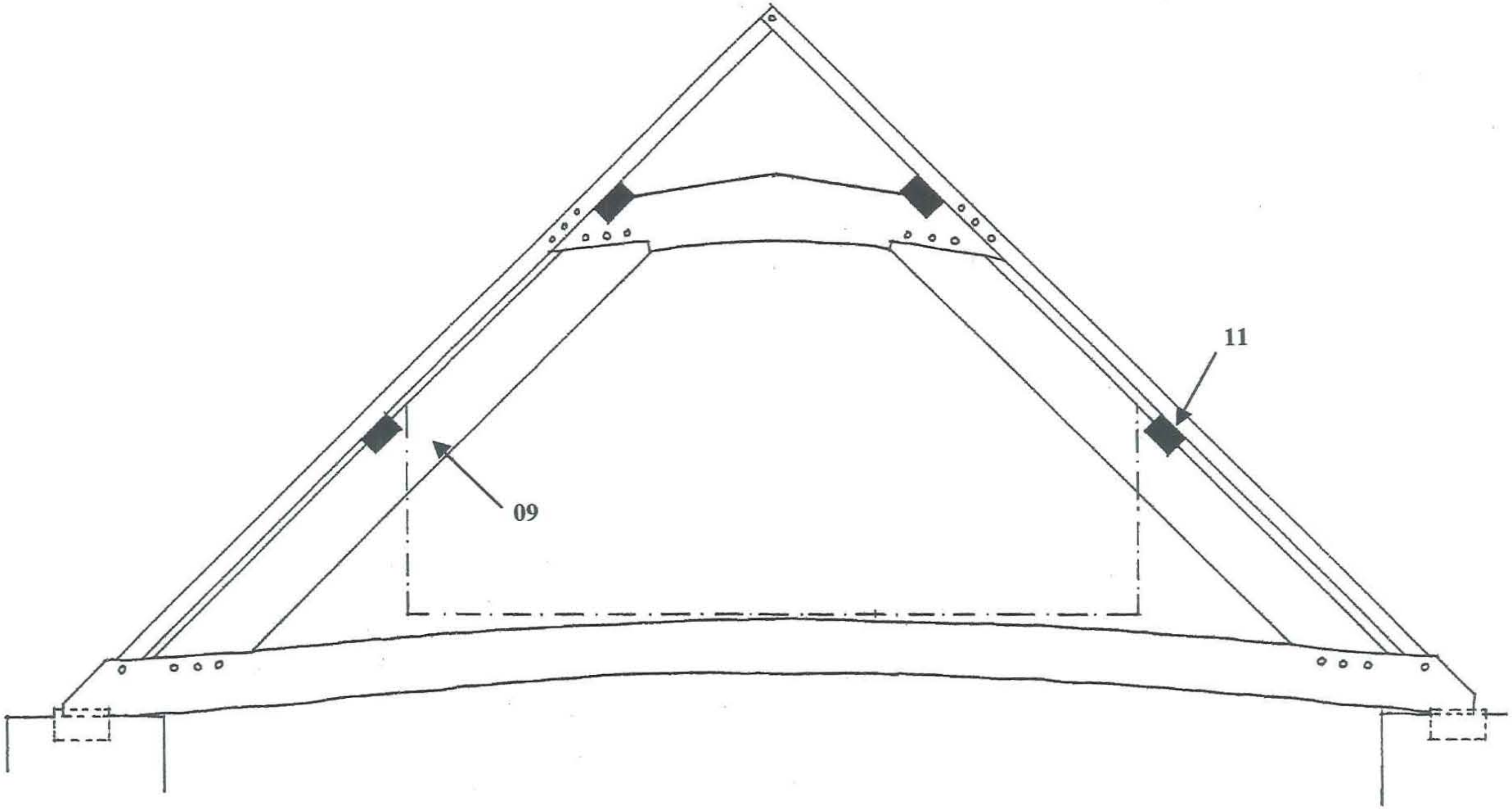


Figure 3e: Drawing to show location of samples from truss 6
(viewed from the east)

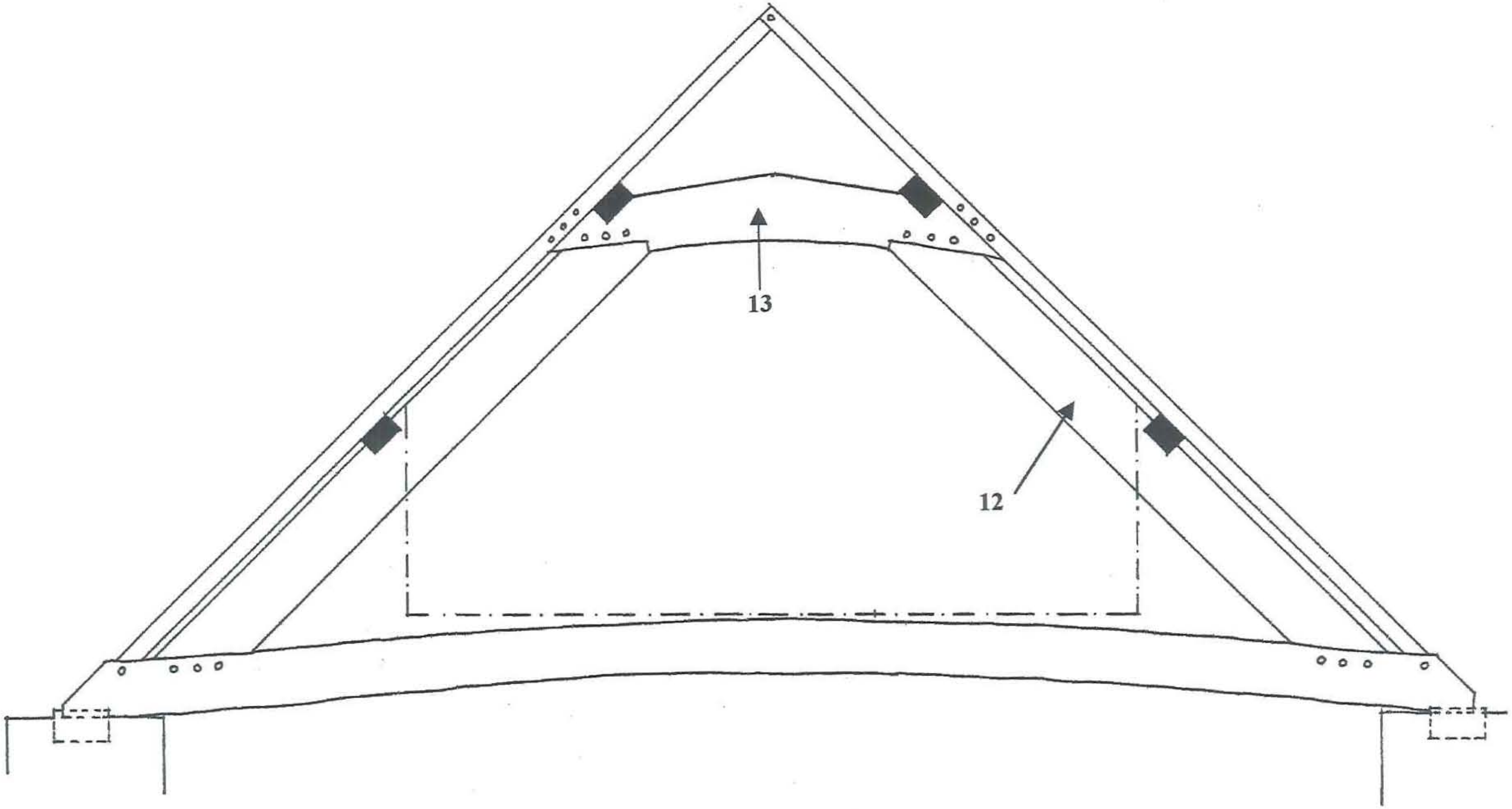


Figure 3f: Drawing to show location of samples from truss 7 (viewed from the east)

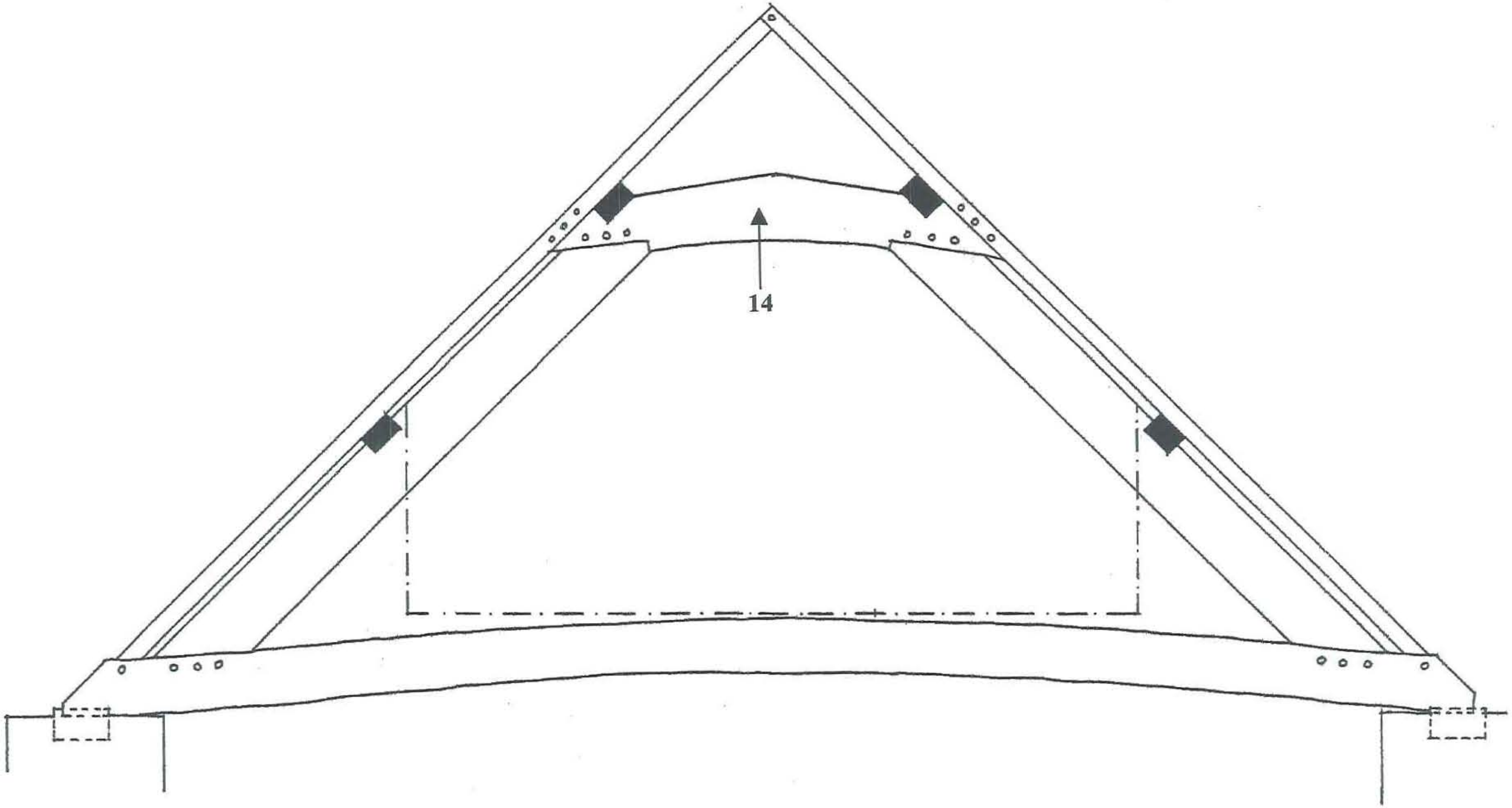
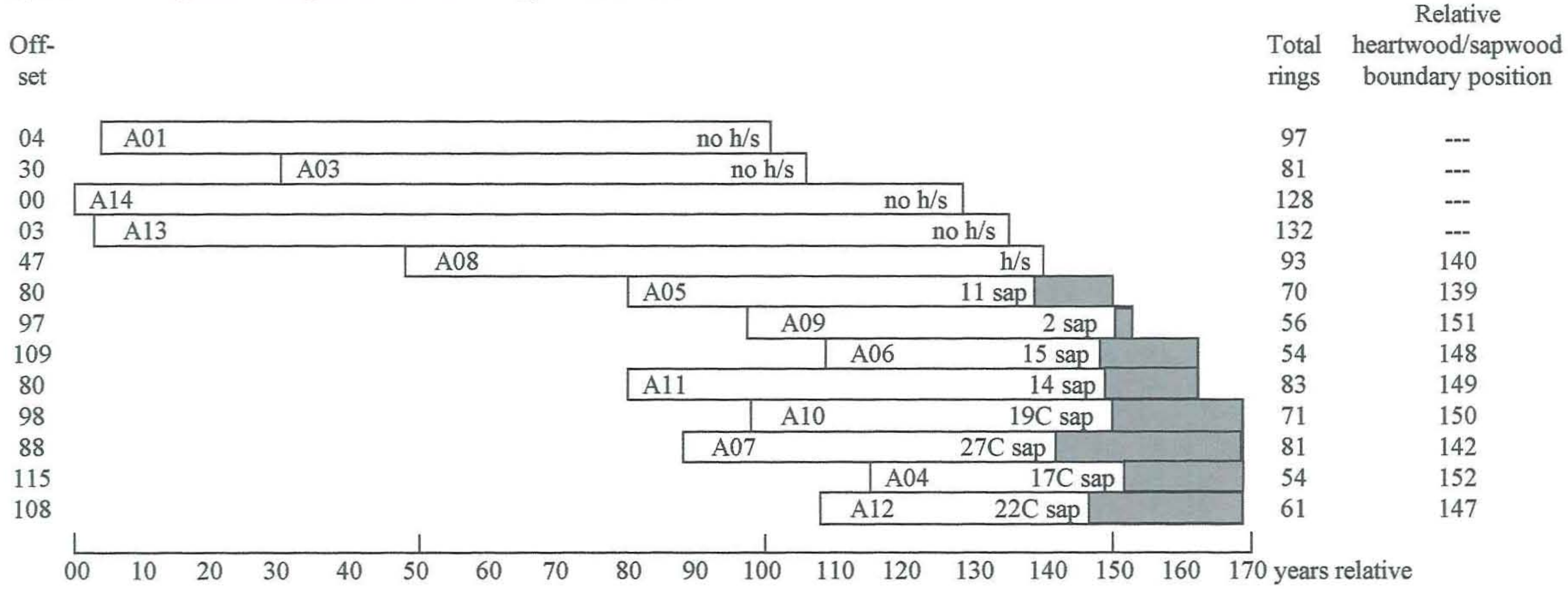


Figure 4: Bar diagram of samples in site chronology TUNASQ01



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Data of measured samples – measurements in 0.01 mm units

TUN-A01A 97
203 162 174 206 113 132 147 174 120 172 130 127 135 108 45 47 59 41 72 81
117 147 140 115 60 100 98 126 164 166 153 143 147 165 144 126 176 105 102 155
118 135 73 205 177 208 128 193 163 144 100 157 209 166 144 149 97 104 105 109
159 144 138 154 152 132 139 125 206 213 176 204 163 194 215 168 190 144 143 190
247 294 211 307 169 166 195 229 223 210 239 206 155 176 142 151 149
TUN-A01B 97
204 167 172 183 125 146 142 188 108 176 123 126 139 108 47 49 56 42 68 80
117 148 135 120 62 94 112 138 172 161 153 143 147 168 143 126 172 102 104 175
135 131 78 208 161 205 132 198 164 154 93 160 207 172 144 151 89 104 110 106
164 125 163 140 155 132 132 125 213 205 178 211 157 201 212 162 193 138 128 192
250 300 220 303 173 154 200 238 217 212 234 222 154 171 150 146 140
TUN-A02A 68
131 73 209 176 208 194 214 192 236 303 402 243 196 165 309 410 218 345 241 330
152 299 241 243 253 196 196 231 200 186 218 193 183 203 155 176 106 103 155 175
134 159 172 222 113 155 152 165 142 180 108 172 233 198 211 167 159 112 107 168
146 295 330 266 199 170 137 109
TUN-A02B 68
135 78 206 167 205 179 221 184 237 313 389 229 218 186 300 397 208 361 240 323
162 287 229 261 233 195 200 238 200 186 204 184 186 190 158 172 84 109 171 176
138 149 198 206 116 133 156 172 144 161 131 194 227 209 259 191 160 132 111 144
142 309 298 257 198 166 131 146
TUN-A03A 81
125 114 184 211 176 160 133 203 190 134 170 136 144 183 125 163 81 212 200 232
194 204 184 238 150 187 193 218 232 239 199 139 143 214 232 182 203 169 133 137
128 187 205 142 163 163 156 185 191 144 277 208 140 200 381 308 270 418 285 307
242 182 202 264 215 234 187 152 139 194 176 141 174 121 223 181 221 273 226 189
209
TUN-A03B 81
119 107 183 213 195 138 154 199 199 123 176 130 128 192 125 152 94 214 214 219
169 221 192 233 156 191 182 198 234 239 191 142 141 213 232 174 193 181 136 139
99 193 216 145 171 172 174 196 208 144 282 196 127 183 362 323 278 410 309 327
255 185 207 261 216 239 183 152 149 186 195 132 182 127 230 179 224 259 233 194
208
TUN-A04A 54
182 242 136 218 182 162 185 161 129 134 178 149 182 152 132 90 148 136 139 147
170 196 198 221 139 158 171 123 105 180 231 208 163 184 208 156 207 219 169 178
210 132 146 118 150 205 231 181 134 87 101 96 88 124
TUN-A04B 54
173 234 132 218 189 161 186 156 132 127 175 154 164 157 137 95 130 148 151 131
170 200 191 224 133 161 183 120 103 176 231 199 172 175 203 166 219 190 186 182
207 130 148 124 136 223 214 192 128 93 100 95 84 131
TUN-A05A 70
78 108 130 135 152 121 95 185 104 106 100 87 92 71 84 96 102 80 94 133
134 135 171 103 91 116 109 137 112 119 120 134 115 106 116 125 152 122 92 139
141 145 94 83 80 88 78 112 140 115 115 112 116 118 107 180 197 196 155 141
145 134 131 111 145 105 114 110 97 123

TUN-A05B 70
114 120 125 132 160 118 94 177 103 108 93 92 84 82 82 90 96 76 92 120
131 148 164 98 105 100 111 132 121 112 121 140 111 113 111 130 142 128 102 130
135 147 89 87 87 83 83 109 136 134 115 107 126 117 112 184 185 193 161 137
141 145 125 125 153 94 118 94 119 151
TUN-A06A 54
109 102 129 169 220 195 194 248 168 201 140 115 125 132 117 112 120 129 200 213
212 128 153 102 116 99 83 125 130 120 92 146 128 110 94 110 116 164 106 122
130 118 180 184 152 167 123 123 114 115 184 120 143 109
TUN-A06B 54
112 95 134 176 212 196 198 253 173 177 163 119 119 140 111 111 120 134 201 205
212 127 151 104 111 93 79 138 124 116 97 145 119 105 86 111 110 173 107 115
143 100 162 181 157 146 148 97 113 138 210 124 178 109
TUN-A07A 81
286 336 337 339 324 285 318 239 243 332 235 305 229 305 283 238 301 243 240 215
230 189 183 186 218 229 160 138 169 155 217 209 182 203 184 129 180 173 120 121
150 147 98 119 93 107 93 83 138 131 86 116 119 146 81 76 74 98 84 83
84 72 76 113 106 88 79 82 74 50 75 75 95 92 55 70 76 63 58 56
81
TUN-A07B 81
277 340 346 348 322 284 321 233 252 330 238 299 223 300 309 264 297 246 242 229
220 185 195 192 210 250 158 139 186 163 228 198 179 222 185 128 183 166 125 131
154 149 108 113 93 101 101 93 136 118 88 122 118 144 99 75 80 95 86 93
89 71 82 112 103 82 81 99 51 64 77 85 96 96 55 66 78 74 47 64
81
TUN-A08A 93
274 182 203 189 162 148 175 151 144 198 151 228 164 122 117 167 234 169 124 197
168 187 120 133 194 182 186 128 114 127 163 174 166 171 151 175 184 216 172 120
237 178 131 143 109 131 150 112 112 127 119 113 167 139 131 164 121 129 196 167
177 136 168 195 225 223 231 212 161 220 130 143 167 157 170 118 108 166 160 107
136 183 197 184 166 209 186 147 210 231 178 258 258
TUN-A08B 93
273 184 193 201 156 146 171 147 144 212 150 212 162 122 140 160 241 171 117 200
173 179 126 138 192 187 178 160 108 128 172 166 157 168 147 166 177 237 174 118
255 173 137 148 98 145 134 113 115 118 125 109 169 149 136 173 116 136 178 171
173 129 167 198 223 232 222 211 163 225 131 134 185 161 167 116 112 169 154 108
143 183 183 187 167 197 188 140 215 238 170 259 206
TUN-A09A 56
332 238 304 223 305 289 238 300 246 242 225 229 237 171 236 263 254 196 174 207
134 203 167 165 187 143 129 152 187 154 171 158 126 96 99 121 134 118 155 173
182 199 122 157 178 134 115 179 232 218 180 193 179 170 245 306
TUN-A09B 56
331 235 300 229 300 309 269 296 243 242 229 220 249 169 238 243 271 187 175 193
139 208 160 165 184 149 132 154 180 138 192 152 131 87 108 118 142 118 150 175
182 195 124 157 193 129 108 173 240 217 189 198 176 169 230 248
TUN-A10A 71
123 134 175 137 153 105 164 147 170 214 187 158 151 186 231 276 235 267 260 213
272 225 212 175 211 138 190 190 168 241 235 210 119 157 122 140 110 97 164 131
133 114 173 150 110 100 106 123 155 109 133 120 109 151 196 150 153 152 93 117
131 201 190 198 150 145 130 132 105 119 177

TUN-A10B 71
124 153 177 130 160 99 163 147 173 209 185 168 146 185 234 271 249 267 264 206
268 238 192 160 208 167 189 184 163 231 244 217 116 163 114 143 111 103 166 135
131 121 167 143 119 103 121 119 143 112 118 129 108 142 186 155 161 155 99 111
121 206 188 208 153 125 137 144 104 101 184
TUN-A11A 83
146 118 93 167 234 172 139 249 192 199 119 129 149 167 182 167 199 195 134 158
129 160 109 79 196 255 263 250 183 166 178 279 221 296 171 130 228 155 236 258
266 196 204 180 269 241 145 194 233 164 91 130 161 201 230 303 197 110 139 119
138 154 95 79 71 96 112 113 130 192 238 345 292 163 165 121 94 102 149 229
225 303 212
TUN-A11B 83
144 125 90 156 239 192 144 245 188 206 113 131 146 157 185 150 184 200 125 151
134 155 102 88 210 303 239 246 189 169 193 258 214 293 162 137 238 153 241 254
254 211 192 169 290 225 144 209 237 159 86 134 170 202 228 298 217 123 128 122
128 161 103 77 72 101 113 119 144 188 249 344 279 170 154 119 88 98 151 227
242 282 223
TUN-A12A 61
252 226 137 100 152 285 223 220 308 270 293 254 295 297 272 175 218 259 222 260
239 288 208 147 167 194 204 198 245 217 229 146 161 95 76 76 108 124 142 134
123 135 125 157 161 153 156 172 123 123 170 189 205 172 155 142 105 80 67 151
151
TUN-A12B 61
242 218 123 103 159 279 245 212 297 265 286 265 276 315 269 184 218 258 203 256
235 295 206 164 167 172 182 205 251 226 251 147 172 99 63 74 103 135 148 133
125 139 126 148 164 155 149 172 118 126 146 181 195 185 146 155 101 74 67 165
157
TUN-A13A 132
350 304 309 332 309 253 282 174 113 90 144 140 122 155 108 111 181 152 137 160
225 206 211 159 179 138 164 175 198 283 251 198 244 188 278 217 214 229 184 151
178 145 185 172 188 159 157 164 169 132 144 152 162 184 163 209 133 111 100 114
150 173 129 146 134 148 120 138 161 177 191 127 173 157 193 158 206 427 219 177
249 258 214 194 235 243 111 186 129 158 193 177 171 188 111 135 125 78 84 86
98 99 129 180 189 178 175 135 178 208 292 220 193 282 117 240 136 184 141 164
143 169 165 140 160 207 210 236 227 208 164 220
TUN-A13B 132
323 321 304 322 312 251 282 166 111 89 135 151 123 149 101 129 176 142 131 169
226 189 217 164 206 145 167 177 193 308 242 183 247 191 278 214 229 219 182 152
193 141 170 174 185 158 156 179 161 120 142 164 167 175 170 201 132 108 103 116
150 170 131 146 140 141 127 129 163 176 199 124 173 161 197 155 189 461 223 169
277 250 212 208 225 245 106 185 131 162 187 183 165 191 106 130 134 73 85 93
95 90 137 191 202 162 178 134 151 209 263 253 184 261 124 235 143 179 140 185
139 171 172 134 169 200 226 225 226 208 163 231
TUN-A14A 128
275 291 223 331 378 276 254 215 216 193 129 109 134 172 216 191 200 255 157 267
142 91 162 226 155 143 126 154 104 122 137 192 305 215 164 205 159 198 199 146
171 122 118 158 137 151 139 175 219 202 159 146 98 180 151 184 171 159 164 145
141 129 126 167 194 155 158 135 178 139 134 182 212 183 127 153 140 172 154 155
277 160 149 247 280 241 223 218 209 97 175 153 207 283 247 189 155 188 187 199
127 148 142 132 187 231 221 283 228 218 167 203 354 393 282 123 215 152 238 254
259 205 210 164 270 244 144 190

TUN-A14B 128
293 281 226 345 380 282 212 216 232 193 134 126 119 180 205 190 208 267 155 262
147 90 142 224 156 148 136 152 106 110 134 198 312 210 159 206 168 200 191 140
172 117 118 190 130 156 147 166 232 221 156 150 109 167 150 184 171 160 166 140
143 125 127 176 196 140 162 142 183 132 139 185 203 174 137 150 140 162 164 155
267 164 156 243 269 242 214 219 218 128 166 151 200 288 263 196 169 189 202 193
136 149 152 119 200 225 226 288 243 209 159 230 344 371 245 109 213 153 238 244
269 197 207 177 272 238 137 196

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.

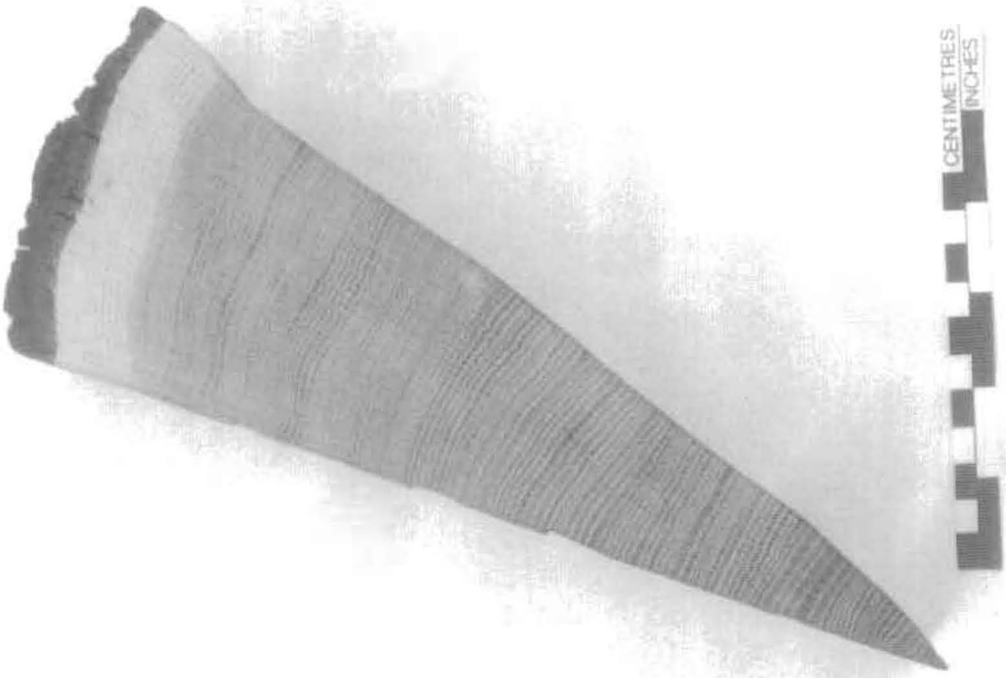


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

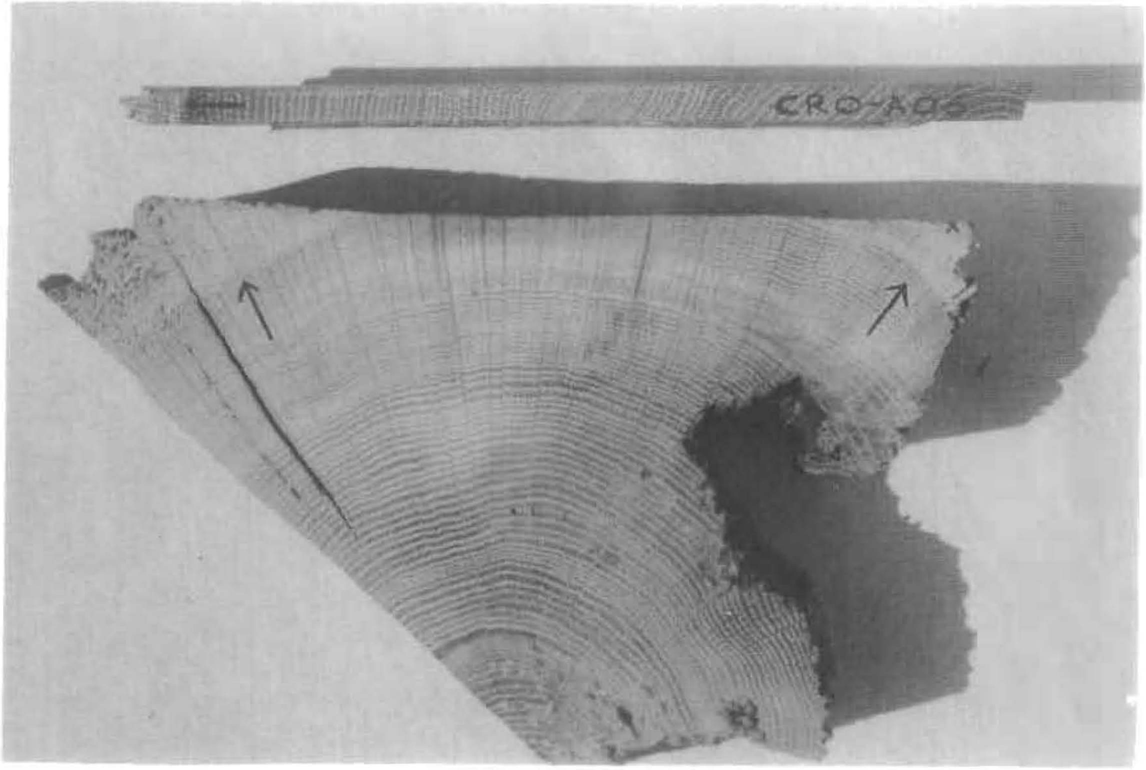


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

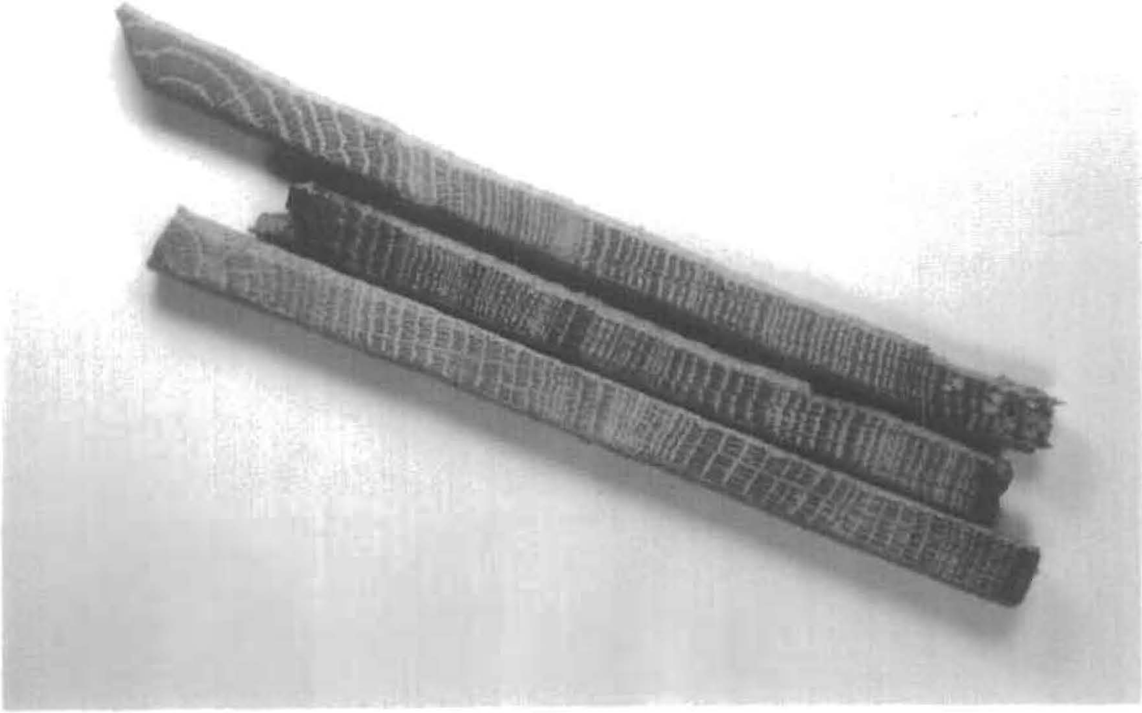


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

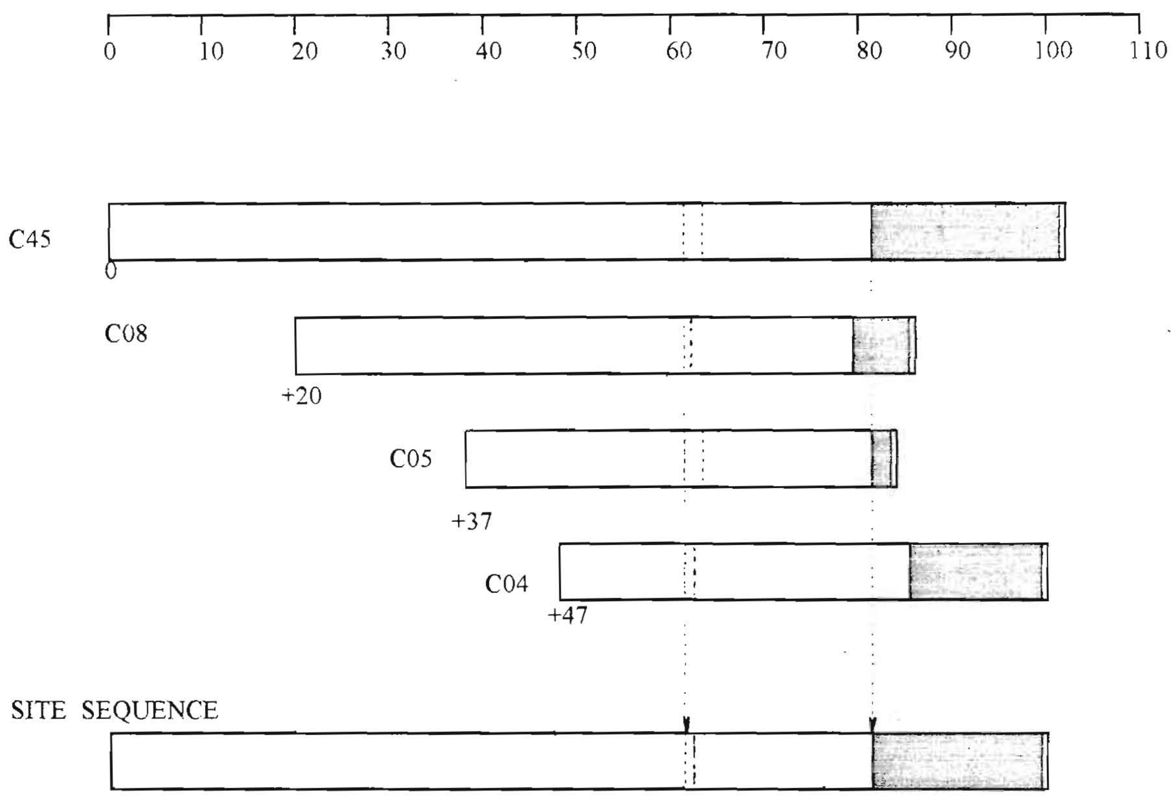


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set 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.

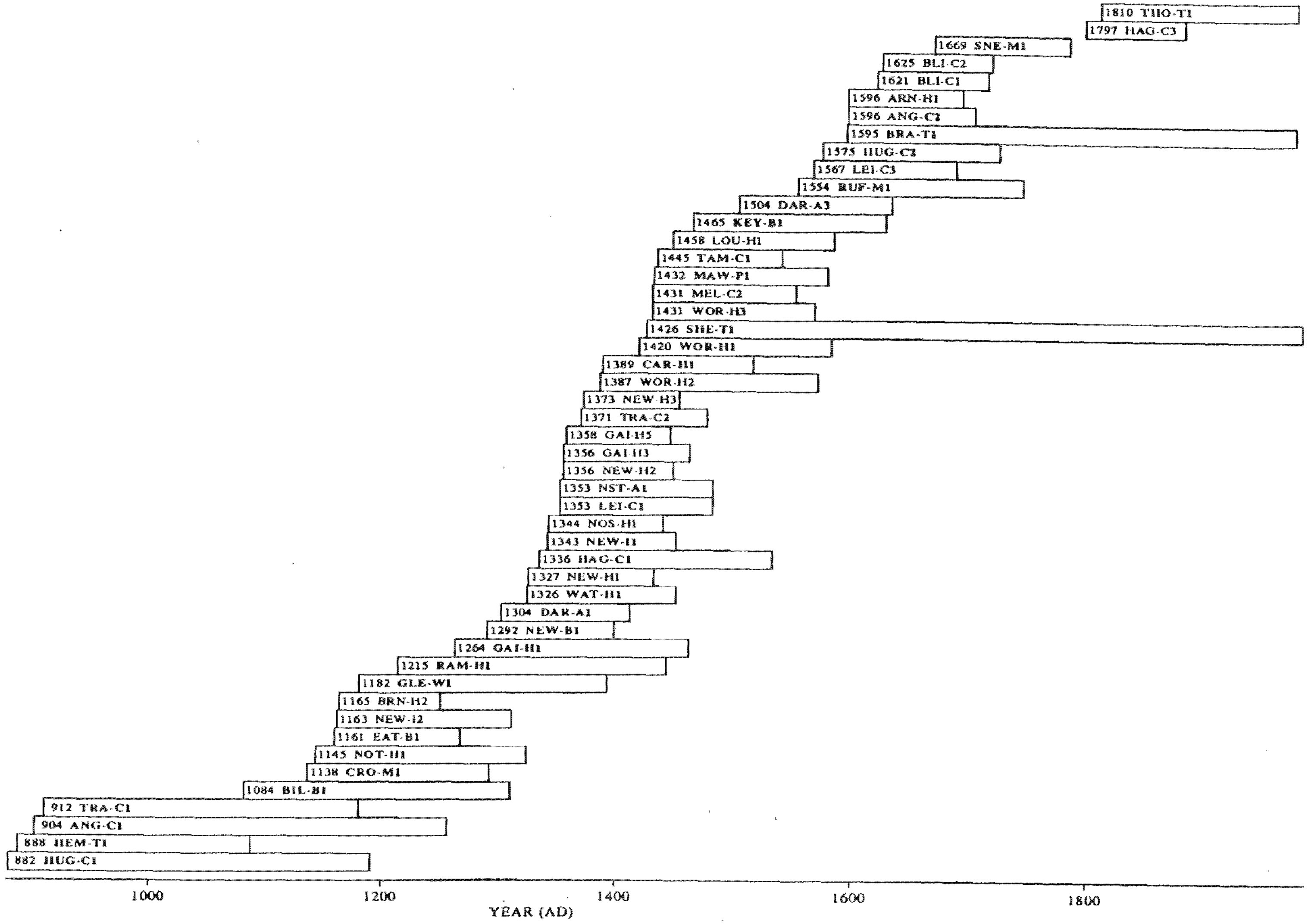


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

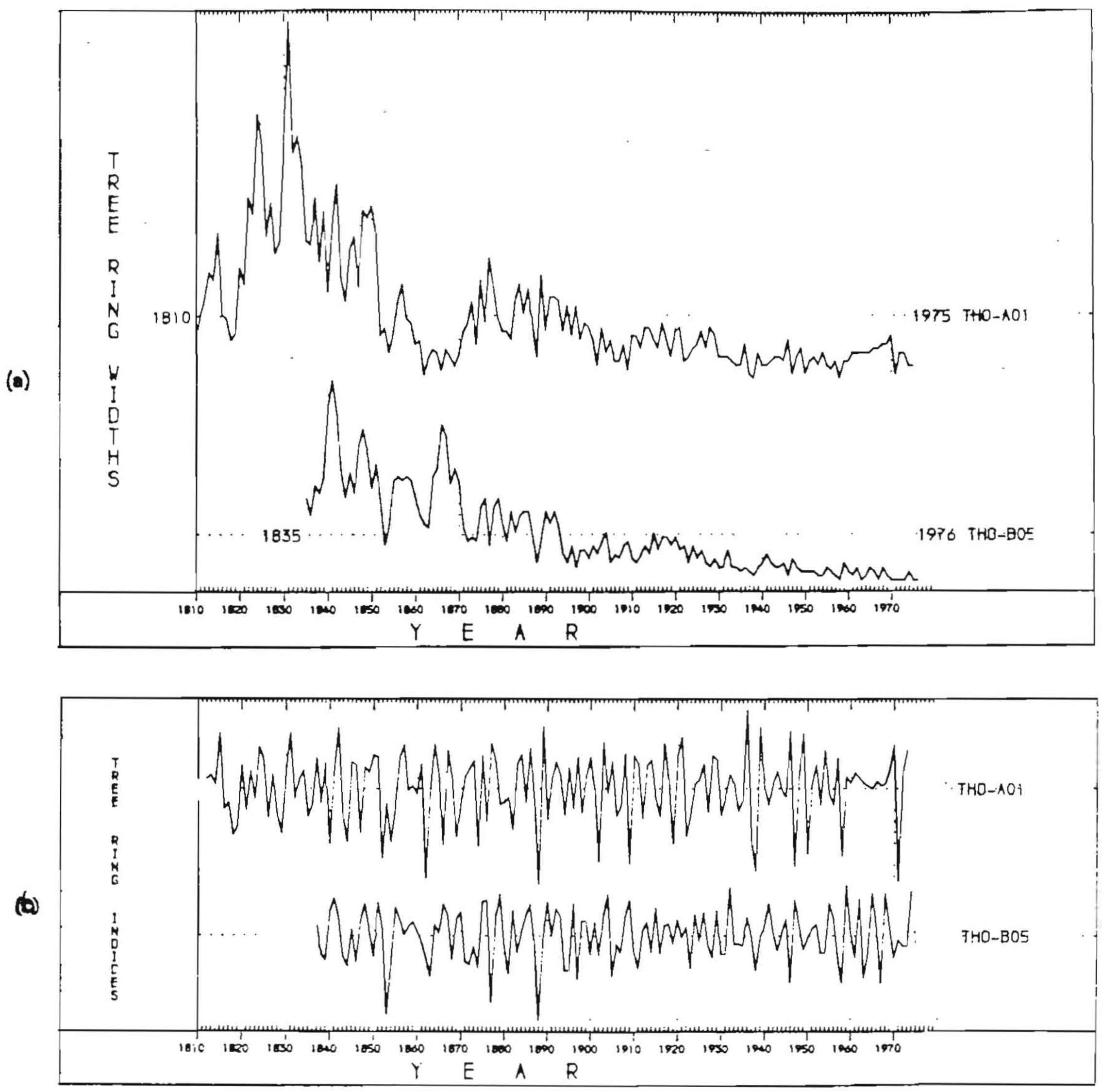


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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