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GRANDY'S KNOWE, BARDON MILL, NORTHUMBERLAND
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Analysis of eight samples from the small number of timbers from the farmhouse at Grandy's Knowe examined here has resulted in the production of a single site chronology, comprising six samples, of overall length of 130 rings. These rings are dated as spanning the years AD 1585–1714.

Interpretation of the sapwood indicates a high probability that two phases of felling are represented. Timbers of the earlier phase (represented by four samples) were probably all cut as part of a single programme of felling dated to AD 1714 (one timber was certainly felled at this date). Timbers of this phase are found in both truss 1 and truss 2, the latter only having timbers of this date.

The timbers of the later phase, represented by two samples and found only in truss1, have an estimated felling date in the range AD 1722–47.

It is possible, therefore, that the AD 1714 timbers represent the primary phase of the farmhouse, truss 2 being an undisturbed remnant of this period, with the AD 1722–47 timbers of truss 1 representing a repair or alteration phase. Alternatively, the primary phase is represented by the material felled AD 1722–47, with timbers felled in AD 1714 being incorporated into the new build. Two other samples remain ungrouped and undated.

CONTRIBUTORS

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ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank Mr Jim Eckersley, builder, and his staff for their enthusiasm and interest in this programme of tree-ring analysis and for their considerable help and cooperation during sampling. We would also like to thank the architect, Mr Kevin Doonan, who provided the drawings used in this report. Finally we would like to thank Martin Roberts, project manager at English Heritage's Newcastle-upon-Tyne Office, for his help and advice during sampling and also for providing background material.

ARCHIVE LOCATION

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DATE OF INVESTIGATION

2008–9

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INTRODUCTION

Grandy's Knowe (knowe here meaning 'hill') is located in the Hadrian's Wall World Heritage Site (NY 7813 6738, Figs 1 and 2), the buildings here being arranged round a rectangular farm yard. The structure of particular interest to this investigation is the Grade-II listed farmhouse, of supposedly early eighteenth-century date, forming the central part of a linear structure located on the northern side of the yard. The house appears to be attached to the east wall of an earlier 'bastle', a type of fortified house peculiar to the England/Scottish border regions, the west end of the farmhouse roof appearing to use the east wall of the bastle for support. A later building, probably no earlier than the late-eighteenth century, and possibly of nineteenth-century date, is attached to the east end of the farmhouse (Figs 3 and 4). A range of three buildings, including a barn between a north and south byre, is located on the western side of the yard, and it is likely that a small structure in the south-east corner was a pig sty.

The bastle at Grandy's Knowe is now roofless, rectangular in shape, and measures 9.15m by 6.7m externally, with walls of large, roughly squared blocks up to 1.3m thick. The walls of the bastle stand to an average height of 1.5m, although the eastern wall and the eastern end of the north wall stand considerably higher, as they have been incorporated into the adjacent farmhouse under investigation. The bastle, thought to predate the farmhouse, is a Scheduled Ancient Monument and is also Grade-II listed.

The farmhouse was originally heather-thatched, but was later given a modern roof. It is roughly rectangular in shape. To both sides of the central door on the ground floor are six-pane sash windows. On the first floor, a smaller rectangular window is located over the doorway and smaller six-pane sashes on either side above those on the ground floor. All the windows have timber lintels. In the north wall, at ground-floor level, a former doorway, later adjusted to form a window, with a timber lintel is located opposite the doorway to the south. It is thought that in its original, early eighteenth-century form, this house had two rooms on the ground and first floors, with a staircase from the entrance lobby (Roberts pers comm). All the buildings on site were undergoing restoration at the time of the dendrochronological investigation.

THE TIMBERS

Only one cruck truss (truss '2'), comprising two blades, two small stub-ties, and a collar, now remains *in-situ* in the middle of the farmhouse (Fig 5), another cruck truss (truss '1'), formerly to the east gable wall and partially collapsed, having been removed during the recent works. This removed truss has been stored on site. This *ex-situ* truss also appears to have comprised two cruck blades, two stub-ties, and a collar (Fig 6). One of the cruck blades to this second truss, however, was composed of two sections of timber spliced and pegged together. They are now disjointed.

It is possible, given the length of the farmhouse and the distance between the two known trusses, that a third truss once existed at the west gable end. It is likely that this truss was dismantled or removed many years ago, and there are now no positively identifiable remnants of it to be seen.

In addition to the timbers of the two trusses, a number of others are to be found here. Most closely associated with the apparently primary timbers are the single purlins to each slope of the roof, between the now *ex-situ* east truss, truss 1, and the still *in-situ* truss 2. There may also have been lengths of purlin between truss 2 and a possible truss 3. This, however, is not certain, and there are no timbers certainly identifiable as such. There is also a small number of loose timbers whose original position and function is unclear.

Whilst in theory other timbers were available, lintels to doors and windows for example, these were either too small for coring to be appropriate, too badly decayed through exposure to the elements, or derived from fast-grown trees and unlikely to provide samples with the minimum of 54 rings necessary for reliable tree-ring analysis. In addition, those timbers not reliably associated with the farmhouse phase being investigated here were excluded.

SAMPLING

Sampling and analysis by tree-ring dating of timbers within the farmhouse at The Knowe (as the building is usually called) was requested by Martin Roberts, Historic Buildings Inspector at English Heritage's Newcastle office, in order to inform statutory advice during restoration. It was hoped that dating the timbers would confirm its age and inform understanding of the development of the farmstead of which it forms part. The current brief focuses on the early phasing of the farmhouse only, the dating of the outshut or the bastle (which in any case contain very little timber) not being required.

Thus, from the small number of suitable oak timbers available, a total of eight samples was obtained by coring. Each sample was given the code GDK-A (for Grandy's Knowe, site 'A') and numbered 01–08. Of these eight samples, two, GDK-A01 and A02, were taken from the two *in-situ* cruck blades of truss '2', the remaining six samples being taken from the *ex-situ* cruck truss '1' and its associated timbers.

Where possible, the positions of these samples were marked at the time of sampling on drawings made by Kevin Doonan, Architects, and provided by English Heritage, or on annotated photographs. These are reproduced here as Figures 5 and 6. Details of the samples are given in Table 1. In this Table, the trusses and other timbers have been numbered from east to west and further identified on a north–south basis as appropriate.

ANALYSIS

Each of the eight samples obtained was prepared by sanding and polishing and the width of its annual growth rings were measured. The data of these measurements are given at the end of this report. The data were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a minimum value of *t*=4.0, a single group comprising six samples could be formed, the samples cross-matching with each other at the off-set position shown in the bar diagram, Figure 7.

The six samples were combined at the indicated offset positions to form site chronology GDKASQ01, with an overall length of 130 rings. Site chronology GDKASQ01 was then compared with an extensive corpus of reference chronologies for oak, cross-matching consistently with a number of these when the date of its first ring is AD 1585 and the date of its last ring is AD 1714. The evidence for this dating is given in Table 2.

Site chronology GDKASQ01 was then compared with the two remaining ungrouped samples, but there was no further satisfactory cross-matching. The two remaining samples were then compared individually with the reference chronologies, but again there was no cross-matching, and these two individuals must remain undated.

INTERPRETATION

One of the six dated samples in site chronology, GDKASQ01, sample GDK-A06, retains complete sapwood. This means that it has the last ring produced by the tree it represents before it was cut down. This last sapwood ring, and thus the felling of the tree, is dated to AD 1714. Judging by the relative position/date of the heartwood boundary on three other dated samples, GDK-A01, A02, and A08, it is probable that the trees they represent were felled in AD 1714 as well.

The heartwood/sapwood boundary on these four dated samples, GDK-A01, A02, A06, and A08, varies by only 11 years, from relative position 90 (AD 1674) on sample GDK-A02 to relative position 101 (AD 1685) on sample GDK-A06. Such similarity in the position/date of the boundary is usually indicative of timbers of a single phase of felling.

Such an interpretation is supported by the degree of cross-matching between the samples, suggesting that in reality these four samples actually represent only two or three different trees at the most. We find, for example, that samples GDK-A01 and A02, respectively from the north and south blades of truss 2 (the west or *in-situ* cruck truss), cross-match with a value of *t*=11.0. A value of this level can be taken to indicate that both timbers may have been derived from the same tree, a probability supported by the observation that the two timbers are each half-trees. Samples GDK-A06 and A08 also cross-match well with each other, with a value of *t*=10.2 being obtained for them. While it is not certain that this slightly lower value represents a same-tree origin for the two timbers, it remains a distinct possibility. The two timbers represented are both from truss 1, the *ex-situ* truss (the scarfed section of blade and stub tie respectively), and both could be half-trees, though both have been trimmed and squared. If they are not half-trees, the value of the cross-match between them would make it probable that the beams are derived from two trees growing close to each other. Indeed, the cross-matching between all four samples would suggest that the trees used were all from the same stand or copse of woodland, an occurrence less likely to be found amongst trees felled at different times.

Two of the dated samples, GDK-A03 and A04, from the main blades of cruck truss 1, have a heartwood/sapwood boundary position that is somewhat later than that of the four samples discussed above, being at 124 (AD 1708) and 121 (AD 1705) respectively. Were the timbers represented by these two samples to have been felled in AD 1714 also, they would have had only nine and six sapwood rings respectively, a figure well below the 95% confidence limit for minimum amounts of sapwood. It is more likely, therefore, that these two samples represent timber felled later, but again, given the similarity of the sapwood boundary on each of them, as part of a single episode of felling. The average date of the heartwood/sapwood boundary on these two samples is AD 1707. Using a 95% confidence limit of 15–40 sapwood rings that the trees might have had would give an estimated felling date range of AD 1722–47. These timbers are likely to be derived from different trees, for not only do they cross-match with each other at a much lower value of t=5.1, but it is likely that while one blade is half a tree, the other blade is almost a whole tree trimmed down.

CONCLUSION

It is likely, therefore, that timbers with at least two different felling dates are found amongst the material examined in this programme of analysis. An earlier phase of felling, dated to AD 1714, is represented by samples GDK-A06 and A08 in truss 1 and by samples GDK-A01 and A02 in truss 2. A later phase of felling is represented by samples GDK-A03 and A04, both from truss 1. Truss 1 thus contains timbers of different dates, AD 1714 and AD 1722–47, while the timbers of truss 2 are of one date, AD 1714.

It is possible, therefore, that the earlier, AD 1714, timbers represent the primary phase of the farmhouse, with truss 2 (represented by samples GDK-A01 and A02) being an undisturbed, intact, remnant of this period. In this interpretation, the AD 1722–47 timbers would represent a repair or alteration phase in which early timbers were combined with later timbers to form another truss (truss 1). An alternate interpretation is that the primary phase of the farmhouse is represented by the timber felled AD 1722–47, with timbers felled in AD 1714 simply being incorporated into a new build. The suggested interpretations indicate an origin in the first half of the eighteenth century for the farmhouse, as anticipated.

Two samples remain ungrouped and undated. This lack of cross-matching does not appear to be caused by any particular problem with the samples, such as narrow, distorted, or complacent rings, or by the ring sequences being too short for reliable analysis. It is possible that the undated timbers, one of them being a loose and unidentified beam, the other being a component of the amalgamated assemblage of truss 1, were felled at different times and may be derived from woodlands in different locations. Such a phenomenon is more likely in a situation, such as we have here, where it can be shown that timbers with different felling dates are present. Such timbers are in effect 'singletons', and while such timbers can sometimes be dated, it is more difficult than with groups of samples in longer, well replicated, site chronologies. A further factor may be the lack of widespread post-medieval reference chronologies for this area against which samples can be compared, a situation which the dated samples from Grandy's Knowe will go some way to improving.

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TABLES

Table 1: Details of tree-ring samples from Grandy's Knowe, Bardon Mill, Northumberland

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
GDK-A01	North blade, cruck truss 2 (west/*in-situ* truss)	90	5	AD 1595	AD 1679	AD 1684
GDK-A02	South blade, cruck truss 2	90	h/s	AD 1585	AD 1674	AD 1674
GDK-A03	North blade, cruck truss 1(east/*ex-situ* truss)	60	h/s	AD 1649	AD 1708	AD 1708
GDK-A04	South blade, cruck truss 1	77	h/s	AD 1629	AD 1705	AD 1705
GDK-A05	Collar, cruck truss 1	55	24C	------	------	------
GDK-A06	North blade, cruck truss 1, scarfed piece	123	29C	AD 1592	AD 1685	AD 1714
GDK-A07	Uncertain *ex-situ* timber	74	21C	------	------	------
GDK-A08	Stub tie, cruck truss 1 (uncertain north/south)	61	h/s	AD 1620	AD 1680	AD 1680

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

Table 2: Results of the cross-matching of site sequence GDKASQ01 and relevant reference chronologies when first ring date is AD 1585 and last ring date is AD 1714

Reference chronology	Span of chronology	*t*-value	
Durham Cathedral, refectory roof	AD 1431–1683	6.5	(Arnold *et al* 2007)
Durham Cathedral, north transept (repairs)	AD 1534–1728	6.3	(Howard *et al* 1992)
Blidworth, Notts	AD 1625–1717	5.9	(Laxton *et al* 1982)
Gunns Mills, Mitcheldean, Glos	AD 1438–1681	5.7	(Arnold *et al* 2004a)
South Central Scotland	AD 496–1975	5.4	(Baillie 1977)
Yorkshire Regional Chronology	AD 440–1823	5.1	(Tyers pers comm)
St Mary's Chare, Hexham, Northumberland	AD 1536–1689	5.1	(Arnold *et al* 2004b)
Middleton Hall, Warwicks	AD 1593–1718	5.0	(Arnold *et al* 2006)

FIGURES

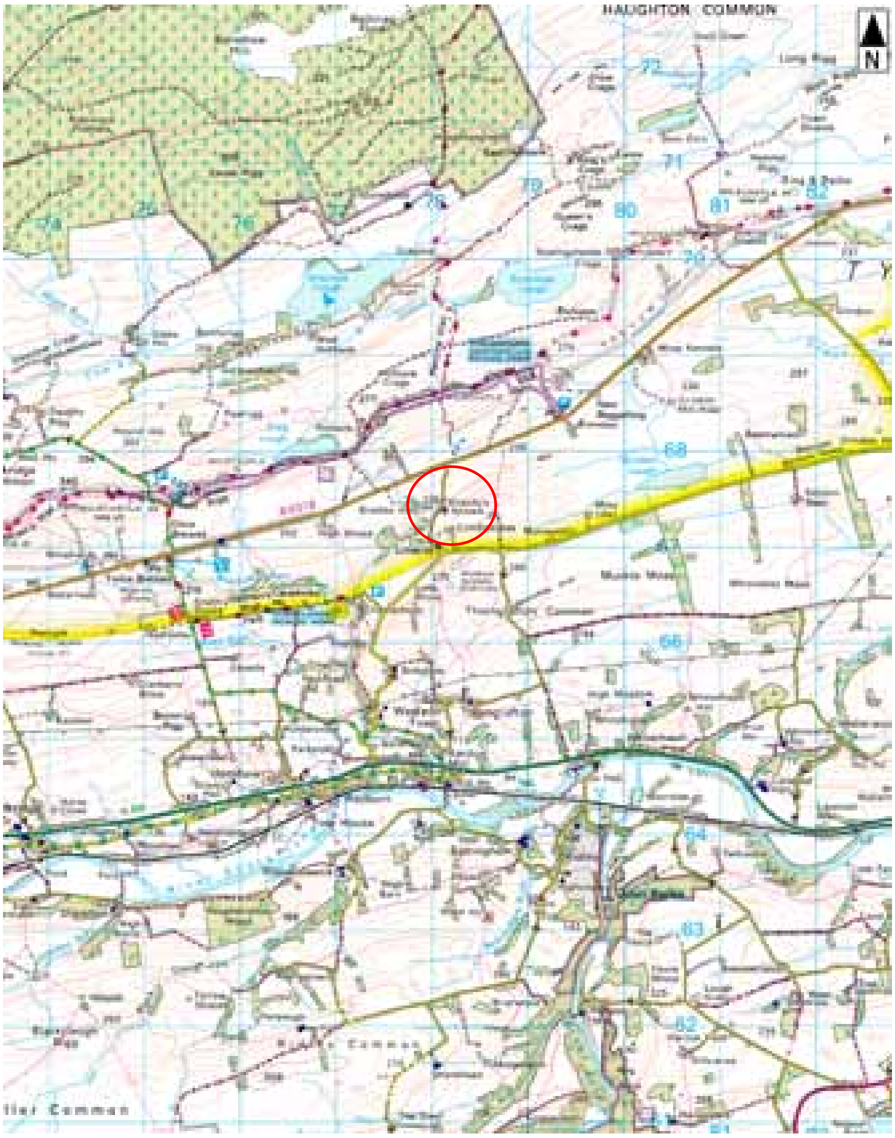


Figure 1: location of Grandy's Knowe, Northumberland (circled)

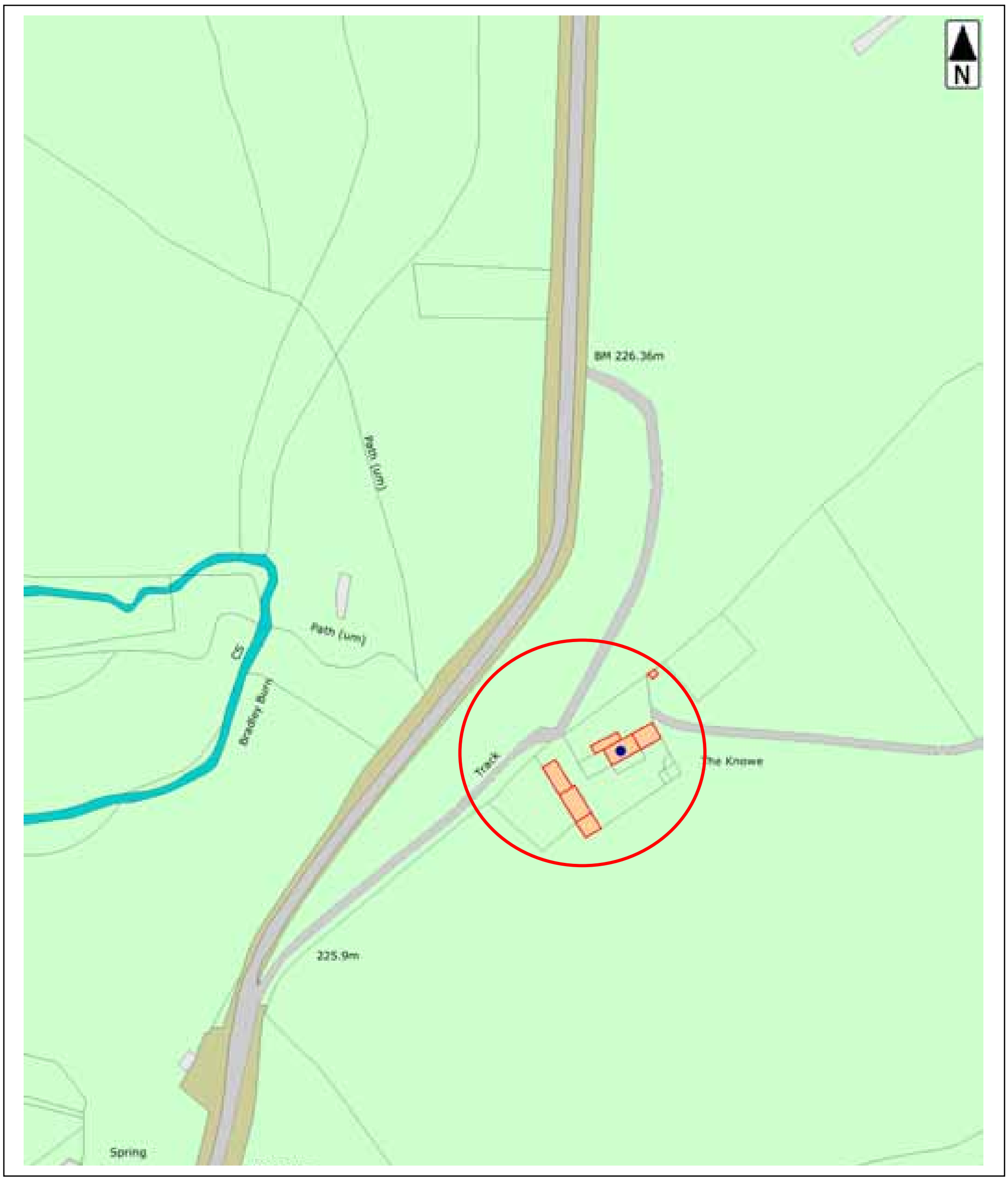


Figure 2: location of the buildings

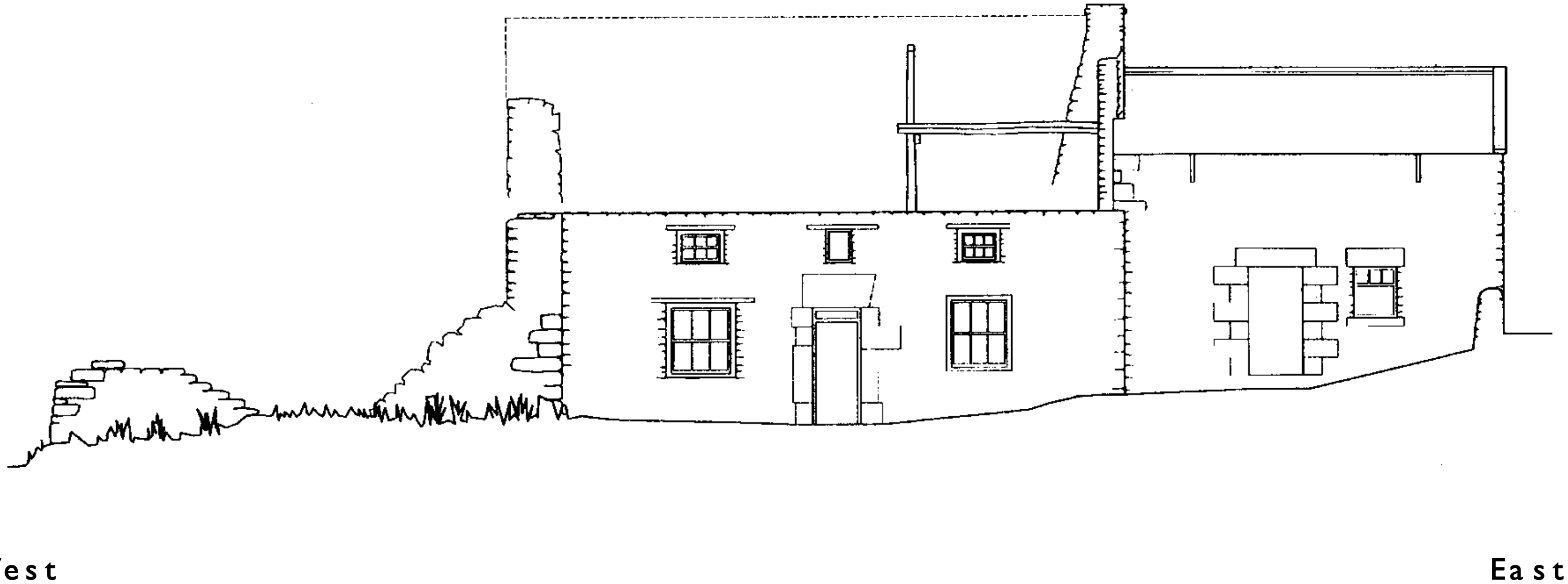


Figure 3: South elevation of the farmhouse with the bastle at the west end and the attached building at the east (after Kevin Doonan, Architects)

Figure 4: View of Grandy's Knowe from the south-west

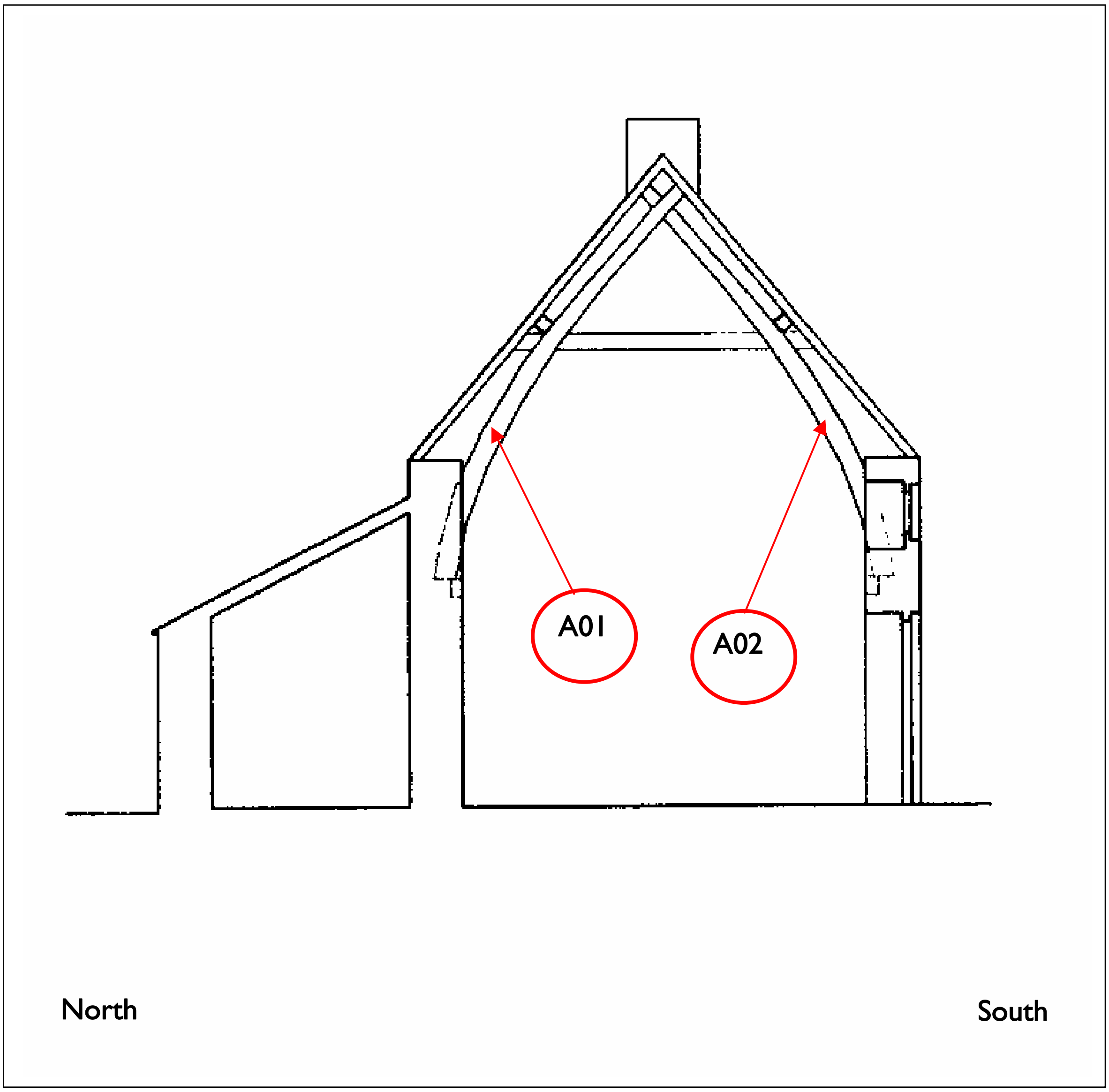


Figure 5: Cross section at truss 2 (in-situ truss) to show sampled timbers (viewed from the west looking east) (after Kevin Doonan, Architects)

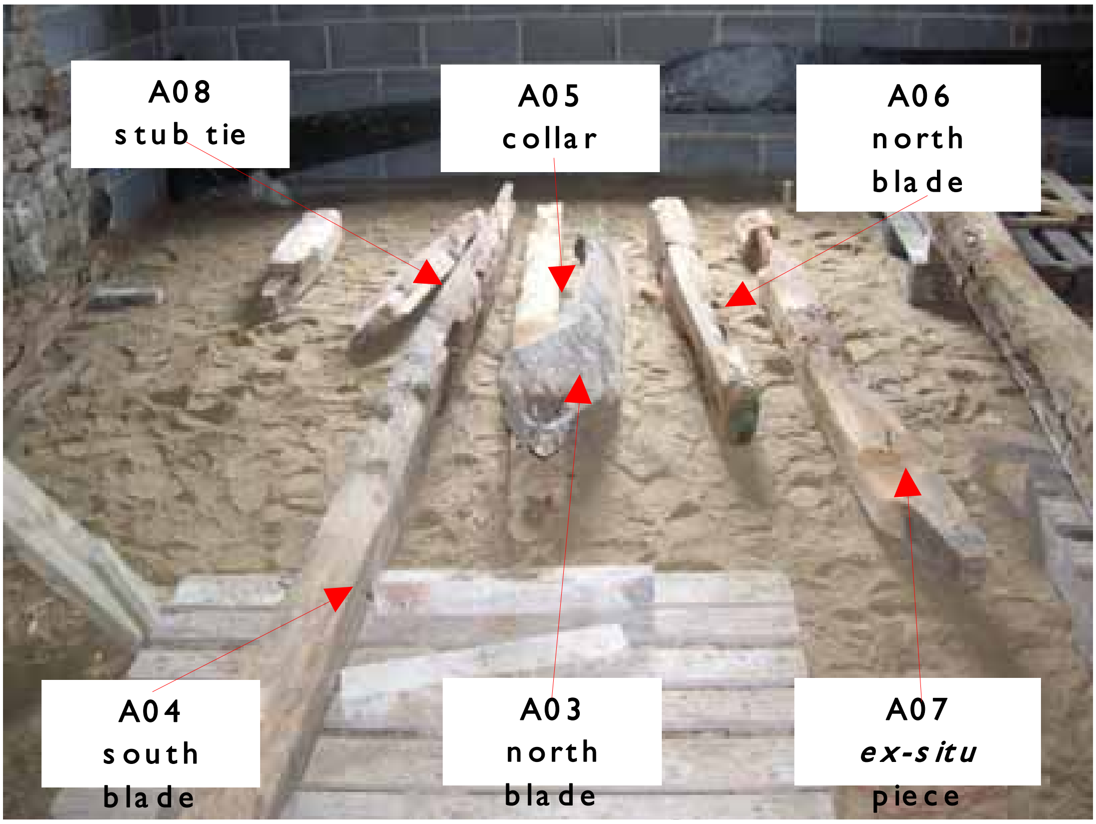
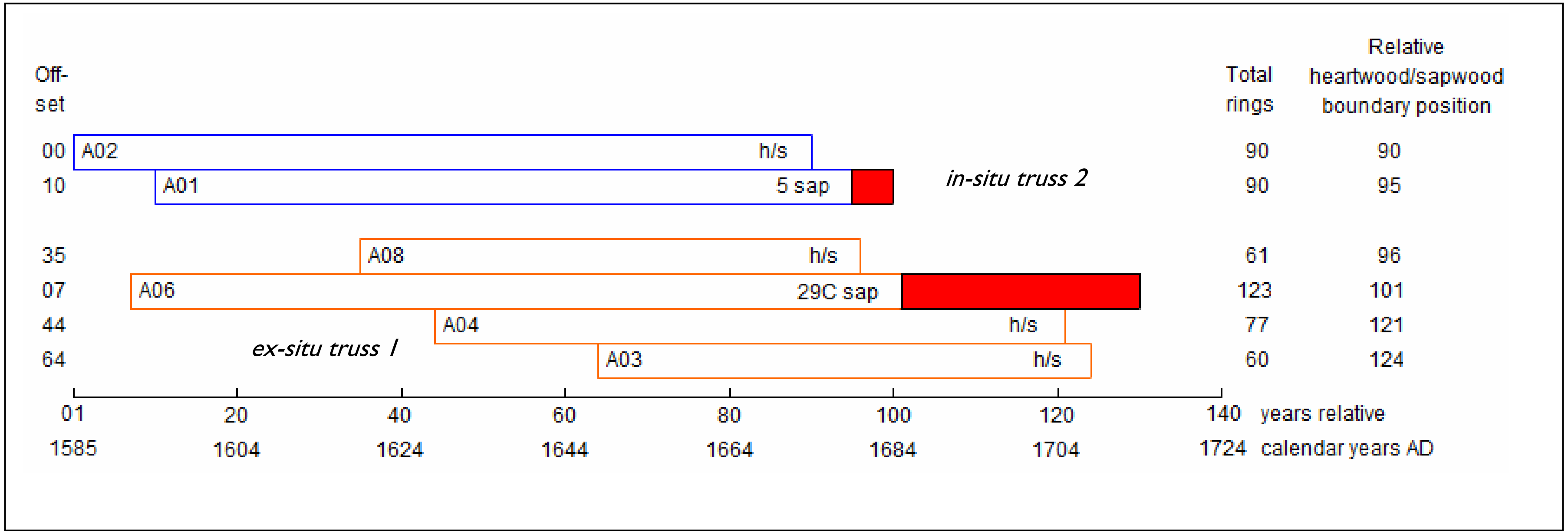


Figure 6: Annotated photograph of the ex-situ east truss, truss 2, to show sampled timbers (exact original position of all timbers not precisely known)



White bars = heartwood rings, shaded area = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing
C = complete sapwood is retained on the sample

Figure 7: Bar diagram of the samples in site chronology GDKASQ01 sorted by sample location and in felling date, or likely felling date, order

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

GDK-A01A 90
334 334 285 255 312 279 279 214 243 276 191 209 211 222 205 249 196 167 208 228
230 222 247 237 205 207 249 237 210 135 89 49 63 71 105 105 112 82 48 36
43 44 72 87 79 107 105 113 68 57 36 44 46 64 72 73 72 70 80 104
119 183 169 220 194 214 152 112 150 209 239 177 195 210 131 174 165 192 197 187
95 65 113 185 205 155 147 140 115 96
GDK-A01B 90
311 328 289 233 318 270 259 209 239 280 193 210 220 215 198 251 189 182 218 242
234 212 236 242 204 215 243 232 220 126 82 53 65 76 108 121 117 77 44 38
39 53 64 93 90 110 114 109 56 42 36 43 53 62 72 78 85 64 81 103
137 175 177 197 189 237 162 115 158 198 259 178 179 213 123 165 157 196 204 183
98 65 118 176 201 163 162 126 114 93
GDK-A02A 90
263 275 249 204 224 279 229 364 262 354 317 216 192 204 188 159 137 115 131 187
137 182 133 155 149 199 126 124 158 145 173 172 176 214 134 152 151 155 136 61
44 41 34 50 84 84 99 55 36 20 16 20 40 70 69 98 98 100 54 33
34 44 49 64 84 90 88 52 93 125 144 233 173 176 177 206 131 107 113 162
192 145 144 157 162 199 187 168 187 189
GDK-A02B 90
286 274 267 216 204 291 223 365 259 342 329 204 197 189 197 164 133 121 131 186
149 165 150 154 154 190 119 129 155 154 173 173 167 210 135 166 152 155 135 60
49 30 41 43 91 96 100 39 32 20 19 31 38 64 69 109 101 94 52 42
31 41 48 76 65 102 85 60 84 115 137 242 156 173 180 231 137 106 118 152
188 145 145 158 171 204 171 166 216 181
GDK-A03A 60
131 140 135 97 120 140 204 230 225 207 184 300 230 360 377 306 268 268 236 282
239 273 216 294 304 240 113 162 156 139 147 131 148 203 179 118 93 95 135 156
181 112 104 122 120 127 116 91 77 74 51 89 97 123 175 124 136 89 68 97
GDK-A03B 60
119 131 139 106 121 139 193 222 228 224 180 296 235 362 367 307 270 288 223 269
224 269 225 282 301 252 116 165 158 149 160 141 135 186 180 119 81 101 130 165
161 120 115 114 125 134 110 99 76 62 59 67 123 123 166 115 135 86 73 103
GDK-A04A 77
352 326 395 360 223 215 257 240 316 330 197 232 274 277 245 136 108 149 175 154
159 193 182 113 141 160 222 238 250 224 171 271 183 143 187 222 138 179 149 137
144 161 122 125 116 70 53 38 62 111 91 101 56 134 64 55 47 43 52 60
82 58 40 43 70 60 62 53 36 42 24 48 59 83 81 88 100
GDK-A04B 77
303 329 385 357 230 218 255 245 319 349 182 248 265 280 246 150 97 151 172 152
173 179 192 105 148 153 236 227 252 221 181 280 182 135 194 217 141 182 144 139
137 158 124 113 123 73 46 39 65 103 102 93 64 138 67 47 46 43 51 72
89 52 42 47 53 58 55 48 50 31 25 48 77 70 76 91 115
GDK-A05A 55
410 315 274 198 112 154 201 207 236 269 161 248 190 109 107 180 174 188 241 155
174 169 151 160 155 179 138 140 125 105 109 93 110 81 75 79 72 67 65 57
52 58 41 39 43 30 41 35 35 34 38 35 32 35 44
GDK-A05B 55
418 322 296 183 122 152 154 230 233 267 147 233 194 99 120 179 211 187 219 138

184 161 152 157 155 169 150 125 124 129 115 98 106 74 76 96 55 76 61 67
52 55 42 38 44 34 40 36 36 34 38 32 30 33 46
GDK-A06A 123
271 214 181 143 92 85 57 78 68 62 53 65 95 102 112 127 118 179 186 178
120 107 138 167 168 152 193 252 176 154 184 178 166 91 78 81 96 119 140 103
89 36 25 23 25 38 68 61 102 98 91 85 44 54 88 94 87 72 73 64
53 73 74 82 88 93 93 100 99 83 96 119 133 151 113 99 137 132 156 173
167 203 167 137 145 192 273 221 131 137 161 98 85 94 80 94 110 119 99 79
54 107 85 92 91 87 91 72 47 69 64 84 95 98 91 106 145 117 76 68
99 94 104
GDK-A06B 123
262 226 178 136 87 87 59 78 70 57 59 54 110 90 113 137 121 167 192 181
113 118 138 164 158 144 200 256 176 156 190 168 172 87 70 82 91 126 139 105
86 32 32 22 27 35 65 67 104 83 96 75 52 44 102 83 111 70 76 59
52 64 80 85 96 93 91 96 101 85 88 115 138 149 115 91 122 124 169 164
177 195 161 134 170 183 274 230 144 129 148 100 101 69 97 91 107 118 101 65
66 107 85 97 90 86 97 56 50 65 63 87 98 99 104 102 139 113 78 83
91 88 97
GDK-A07A 74
150 179 195 372 97 119 141 132 156 214 132 163 143 60 66 132 205 235 184 203
194 105 104 135 168 121 139 140 162 169 150 137 118 127 137 142 121 109 110 118
107 142 152 186 146 186 162 136 137 137 148 144 142 137 125 132 118 112 118 119
108 83 86 92 97 103 89 89 102 87 76 72 76 94
GDK-A07B 74
107 165 187 377 112 113 147 135 163 204 112 161 145 65 66 130 222 217 163 202
223 88 104 134 139 118 140 139 152 187 154 142 105 134 136 137 124 113 112 121
105 135 161 171 155 200 169 157 133 128 149 136 148 142 104 144 112 119 123 122
101 77 95 84 99 111 85 82 106 88 83 73 77 109
GDK-A08A 61
355 290 306 280 260 144 126 133 118 210 147 143 121 56 37 36 37 69 102 103
158 142 108 89 52 44 96 78 95 89 110 72 54 91 109 110 172 138 126 132
160 101 88 93 117 121 120 110 164 151 217 210 251 279 208 228 136 168 259 169
132
GDK-A08B 61
357 290 303 286 264 154 122 131 109 219 150 135 125 60 34 31 46 81 124 112
167 144 103 86 52 55 96 81 92 86 100 59 55 88 101 103 160 130 130 120
165 100 73 102 120 122 101 120 162 159 225 211 238 260 234 226 134 181 255 180
113

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

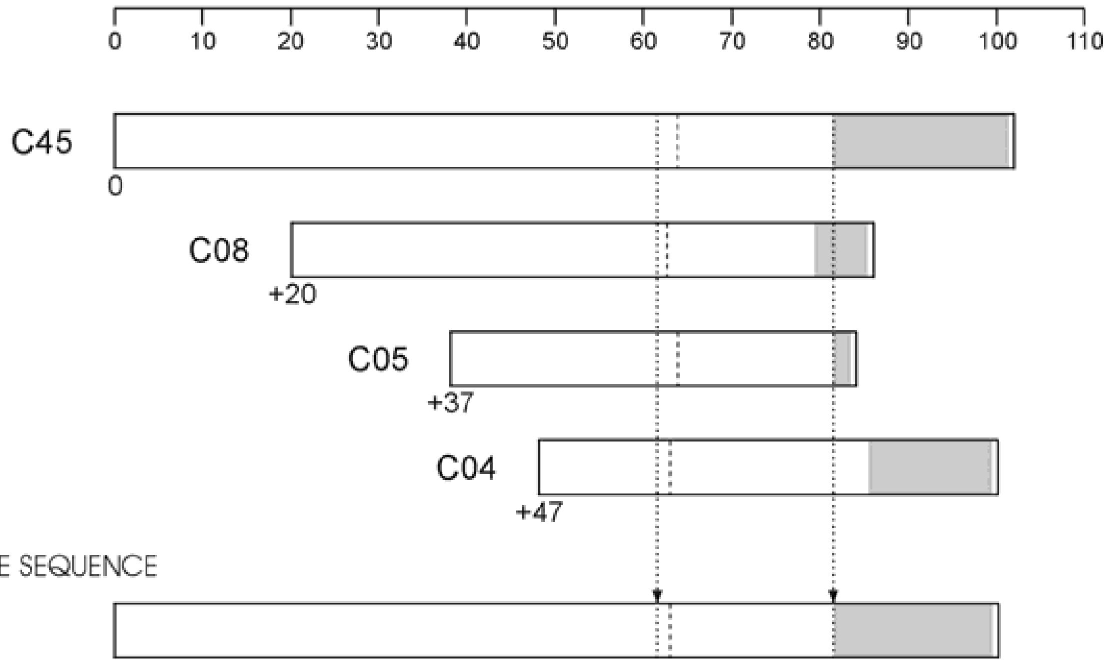


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

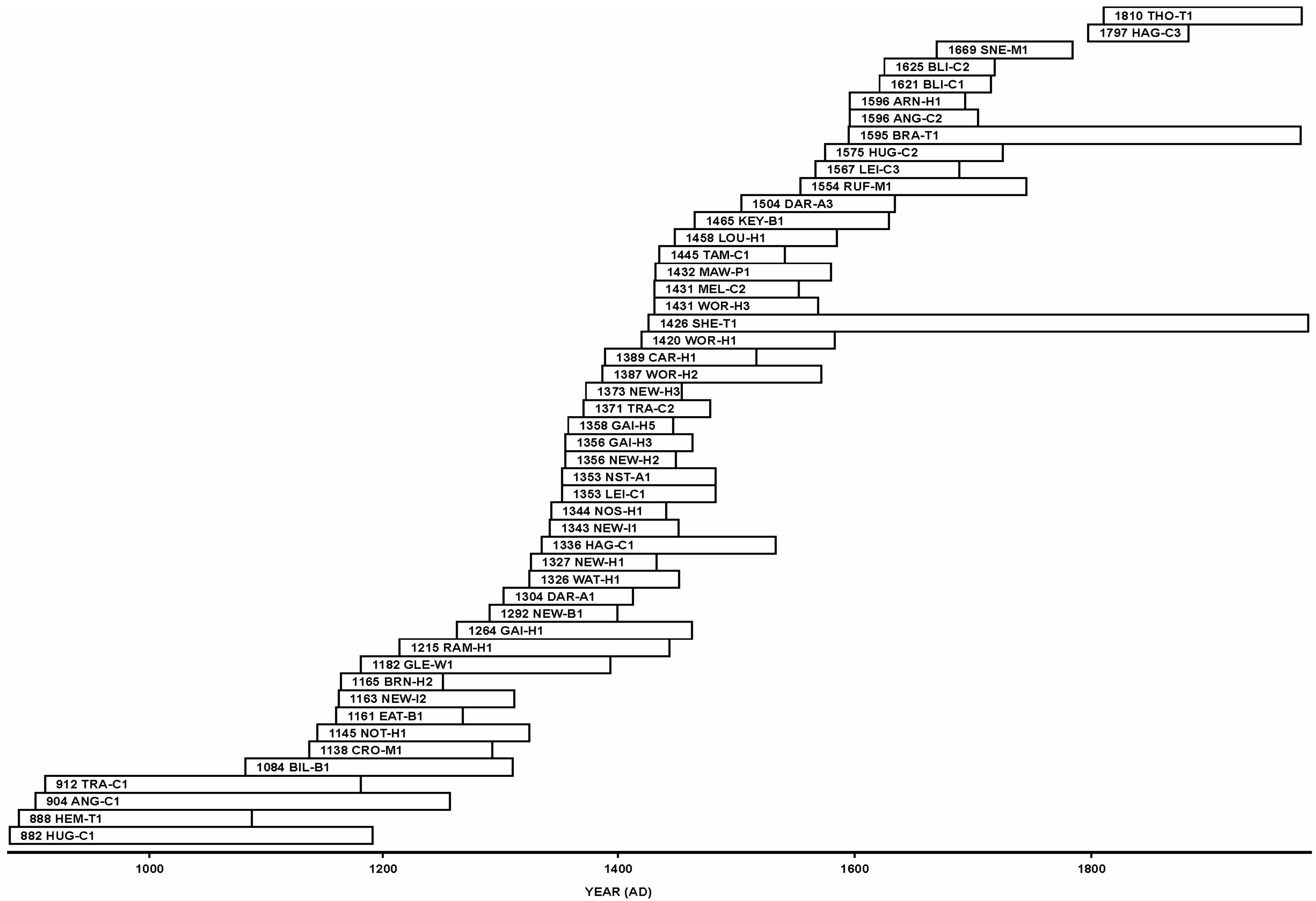
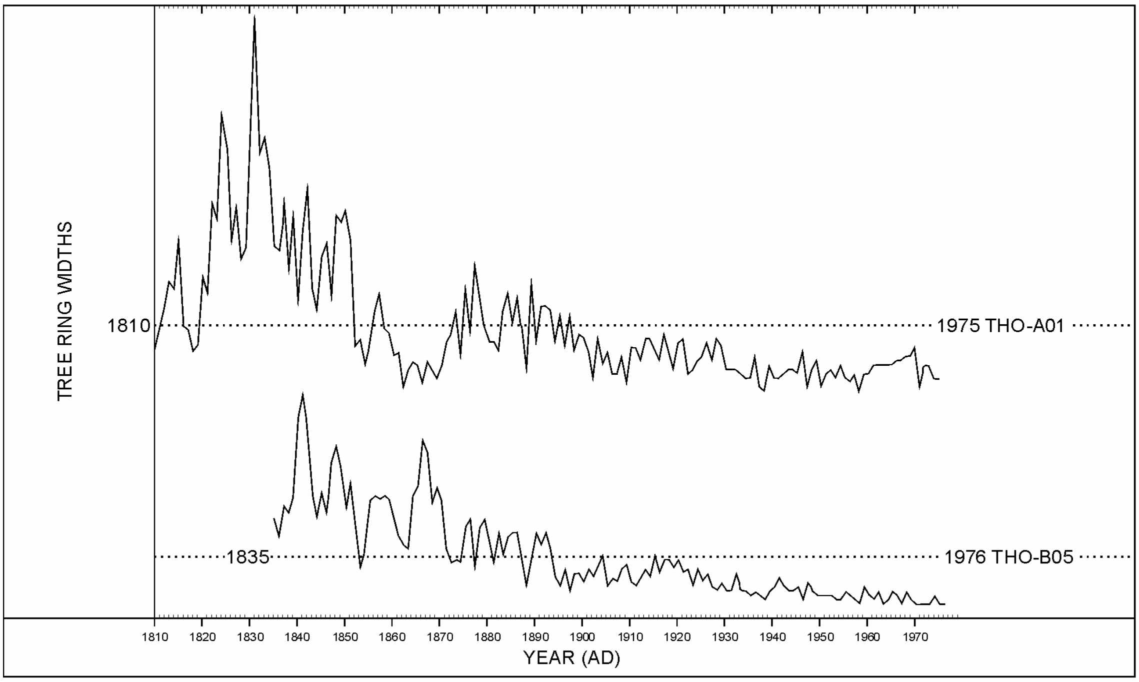


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

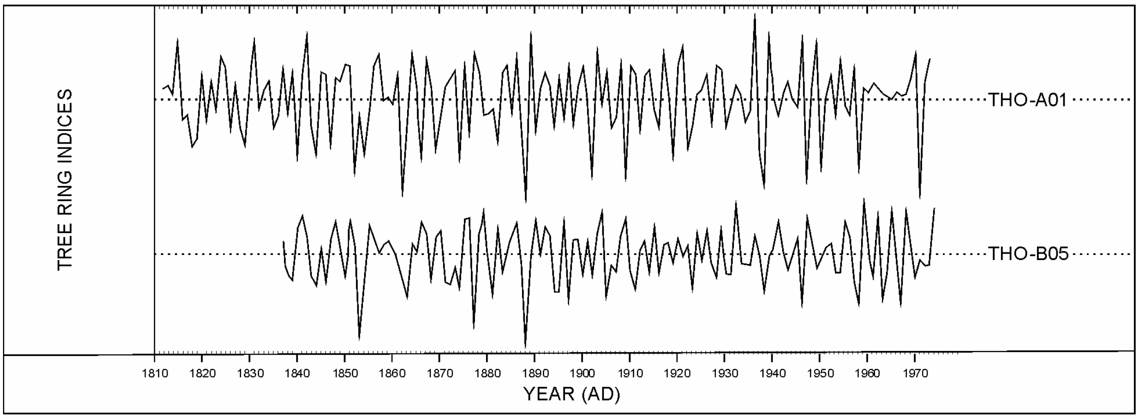


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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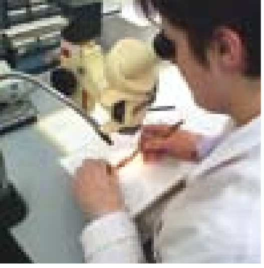
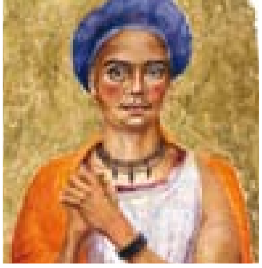



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