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ST MICHAEL'S MOUNT, MARAZION, NEAR PENZANCE, CORNWALL
TREE-RING ANALYSIS OF TIMBERS FROM THE CHEVY CHASE ROOM

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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Research Department Report Series 67/2007

St Michael's Mount, Marazion, near Penzance, Cornwall Tree-Ring Analysis of Timbers from the Chevy Chase Room

Alison Arnold and Robert Howard

Summary

Dendrochronological analysis was undertaken on samples taken from the roof structure in the Chevy Chase room of this building.

No timbers were grouped and attempts to individually date the samples were unsuccessful.

Keywords

Dendrochronology
Standing Building

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Introduction

St Michael's Mount in Mount's Bay, Marazion, near Penzance (Fig 1; SW51492983) is believed to have been an important trading post from as far back as prehistoric times. The Mount is an island at high tide, only accessible by boat. However, at low tide a granite causeway is revealed, allowing pedestrian access. The island has a small harbour on its northern shore, with houses, shops, and restaurants.

It is believed that in AD 1044, Edward the Confessor founded a chapel on the Mount in a grant to the Benedictine Abbey of Mont Saint-Michel. Following the Norman Conquest, William the Conqueror gave the majority of the west of England to Robert, Count of Mortain, who in turn granted St Michael's Mount to the Norman Abbey of Mont Saint-Michel. In AD 1135 the first priory on the Mount was established by Bernard of Le Bec. Following extensions and remodelling in the fourteenth, fifteenth and later centuries, the Mount is now dominated by the Grade-1 listed priory castle (Fig 2).

The castle is of a rather irregular plan, as necessitated by the rocky outcrop upon which it is built (Fig 3). The earliest domestic parts are contained within an L-shaped block, which comprises a south range and west entrance range. The entrance range has projecting towers at either end, with the entrance on the left hand side of the range between the towers. To the right of the entrance is the Armoury, once a hall. Projecting from the left-hand tower is a thick buttress which may possibly be the remains of an outer entrance or gatehouse. Behind the Armoury and set at right angles to it is the Church of Saint Michael. In the late-fifteenth century a Lady Chapel was built adjoining the north-east corner of the church. This was remodelled in the AD 1760s and contains the Blue Drawing Room.

In the outer angle between the west and south range is a square block; thought to have once been a tower with garderobe, it is now known as Sir John's Room. Behind this is a lobby and behind the lobby is the Library, an eighteenth-century remodelling of another tower. At the rear right-hand corner of the Breakfast Room is the former monks' refectory, which has been known as the Chevy Chase Room since the seventeenth century. Around the room is a seventeenth-century frieze depicting the Chevy Chase, a seventeenth-century coat of arms and eighteenth-century plasterwork. The roof structure in the Chevy Chase Room is thought to be the only surviving medieval roof in the building. It is of arch-braced type, and is believed to be a fifteenth-century re-roofing (Fig 4).

The nineteenth century saw much remodelling and extension of the castle, with terraces being added to fill the south-east angles and north and north-west of the church. In this way the amount of accommodation was greatly increased. The south-east block comprises reception rooms and chambers over a basement entrance floor. The area north of the church was the service wing, including the kitchen (now the Museum). Above the terrace level there is a link building from the Blue Rooms to the Long Passage, south of the church. This leads to a large stair turret in the angle between the church, the Breakfast Room and the Chevy Chase Room.

In AD 1660 St Michael's Mount passed into the ownership of the St Aubyn family, who occupied it as an occasional residence, mainly during the summer months, until the eighteenth century, when it became their permanent residence. In AD 1954 it was given to the National Trust, on the understanding that the St Aubyn family retained a 999-year lease to live in the castle.

The description above is taken from the castle's listing description (*www.imagesofengland.co.uk*) and the website *www.cornwall-online.co.uk/heritage-trail/heritage-national-trust/stmichaelsmount*.

Objectives of the tree-ring analysis

Sampling and analysis by tree-ring dating of the Chevy Chase Room was commissioned and funded by English Heritage. Tree-ring dating has been requested by Francis Kelly, Historic Buildings Inspector at English Heritage's South-West office, to inform statutory advice in the context of the current programme of repairs. The roof trusses were thought of as rare medieval survivals and it was hoped that the results would provide a date for the construction of the roof.

Acknowledgements

The Laboratory would like to thank all at the English Heritage Scientific Dating Section and Cathy Tyers of the University of Sheffield Dendrochronology Laboratory for their advice and assistance. Thanks are also given to Gary Early, site agent at St Michael's Mount, for organising access and the erection of scaffolding, and to Eric Berry, for his on-site advice. Figures 5–11 were provided by Nigel Thomas of Cornwall County Council.

Sampling

Upon initial surface inspection of the timbers they could be seen to have relatively wide growth rings, and it was uncertain whether they would have sufficient rings to make secure dating a possibility. However, following on-site discussions, the decision was taken to sample in the expectation that at least some of the samples would have the minimum required number of growth rings (54 rings) and that potentially relevant local reference data was available from Godolphin House, which lies approximately 10km east of St Michael's Mount (Tyers and Tyers forthcoming). As such thirteen samples were taken from the timbers from the roof structure. Each sample was given the code SMM-C (for St Michael's Mount, Cornwall) and numbered 01–13. The trusses have been numbered from east to west (Fig 5) and the position of all samples was noted at the time of sampling and has been marked on Figures 6–11. Further details relating to each sample can be found in Table 1.

Analysis, Results, and Interpretation

As suspected, the majority of the samples had less than the usual minimum 54 rings, but it was decided to measure all samples with more than 40 rings in the hope that with a greater number of sample sequences there would be an increased chance of internal cross-matching. In this way, the possibility of producing a well-replicated site sequence, of reasonable length, to match against the reference chronologies would be improved. This approach has, on occasion, been successful where relatively extensive sampling produced at least some timbers with reasonable length ring sequences and local reference data were also available (Groves 2005). Four samples were still rejected as having less than 40 rings. The remaining nine samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were then compared with the others by the Litton/Zainodin grouping procedure (see appendix).

No grouping between samples occurred and attempts to securely date the samples individually by comparing them against the reference chronologies for oak were unsuccessful.

Discussion

Prior to the tree-ring analysis being undertaken on the roof of the Chevy Chase room it was thought to be a fifteenth-century re-roofing. It is unfortunate that tree-ring analysis has been unsuccessful in this instance, with none of the sampled timbers being securely dated, thus neither confirming nor refuting this date.

There is nothing particularly unusual about the growth patterns of this group of samples, being neither unduly complacent or compacted, something which may have masked the overall climatic signal necessary for successful dating. Therefore, the most likely reason for this lack of dating is the relative shortness of the ring sequences (the majority of the measured samples have less than 55 rings) and the fact that no intra-site matching has occurred. Generally, the longer and better replicated a site sequence is, the greater the chance of successful dating. It is notoriously difficult to date individual samples, a fact compounded by the problematic nature of dendrochronological analysis in the south-west.

Bibliography

Groves, C, 2005 *Dendrochronological Research in Devon: Phase I*, Centre for Archaeol Rep, 56/2005

St Aubyn, J, 1978 *St Michael's Mount Illustrated History and Guide*, St Ives

Tyers, C, and Tyers, I, forthcoming *Godolphin House, Godolphin Cross, Cornwall: Scientific Dating Report - Tree-Ring Analysis of Timbers*, EH Res Dept Rep Ser, -

Table 1: Details of tree-ring samples from St Michael's Mount, Cornwall

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
SMM-C01	South principal rafter, truss 2	42	--	----	----	----
SMM-C02	Collar, truss 2	57	h/s	----	----	----
SMM-C03	North upper arch brace, truss 2	NM	--	----	----	----
SMM-C04	South principal rafter, truss 3	44	--	----	----	----
SMM-C05	North upper arch brace, truss 3	43	--	----	----	----
SMM-C06	North principal rafter, truss 4	48	h/s	----	----	----
SMM-C07	South principal rafter, truss 4	43	--	----	----	----
SMM-C08	North principal rafter, truss 5	NM	--	----	----	----
SMM-C09	South principal rafter, truss 5	NM	--	----	----	----
SMM-C10	North principal rafter, truss 6	54	--	----	----	----
SMM-C11	North upper arch brace, truss 6	86	--	----	----	----
SMM-C12	North principal rafter, truss 8	48	02	----	----	----
SMM-C13	South principal rafter, truss 8	NM	--	----	----	----

*NM = not measured
**h/s = the heartwood/sapwood ring is the last ring on the sample

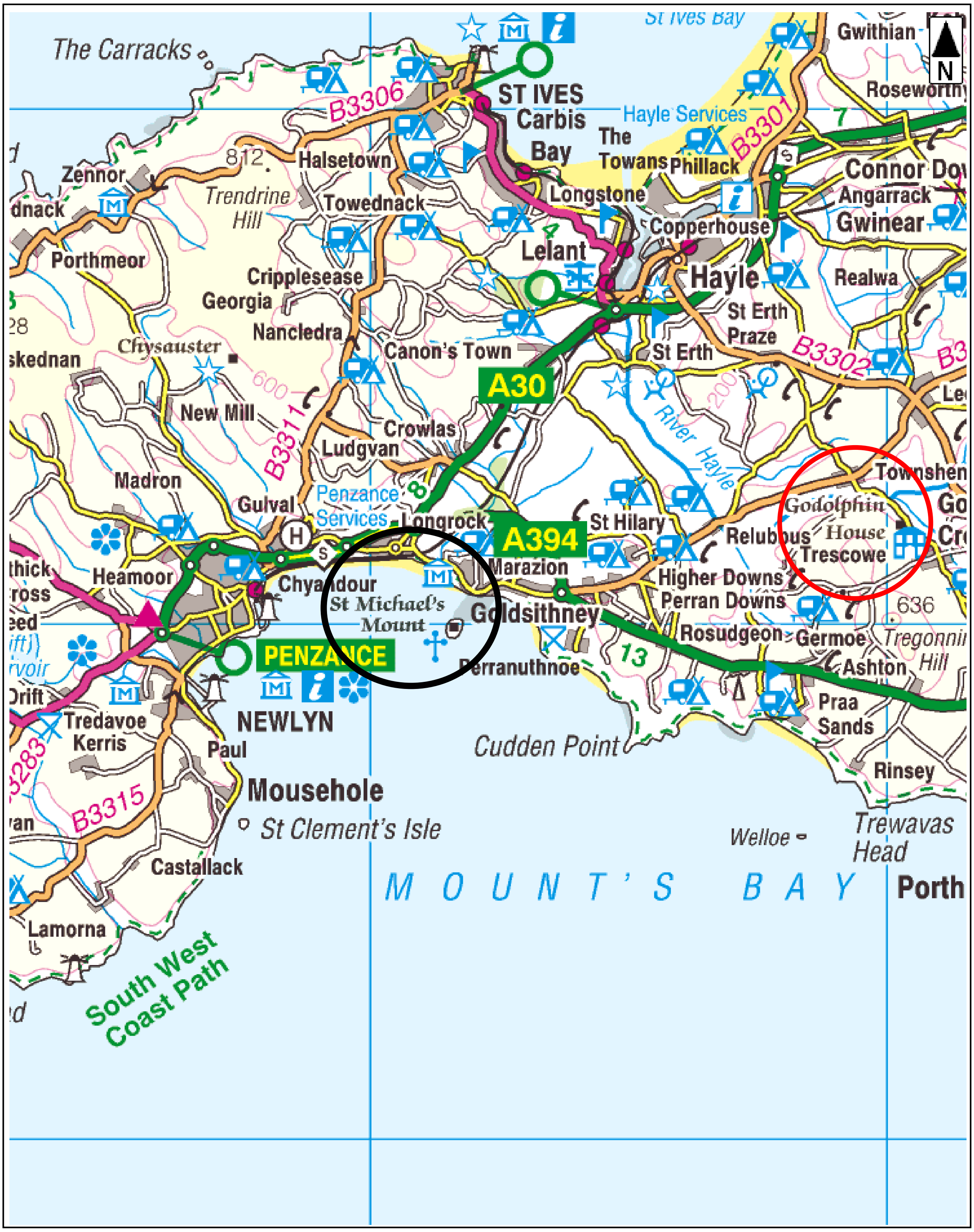


Figure 1: Map to show the location of St Michael's Mount (circled in black); also shown is Godolphin House (circled in red),

Figure 2: St Michael's Mount

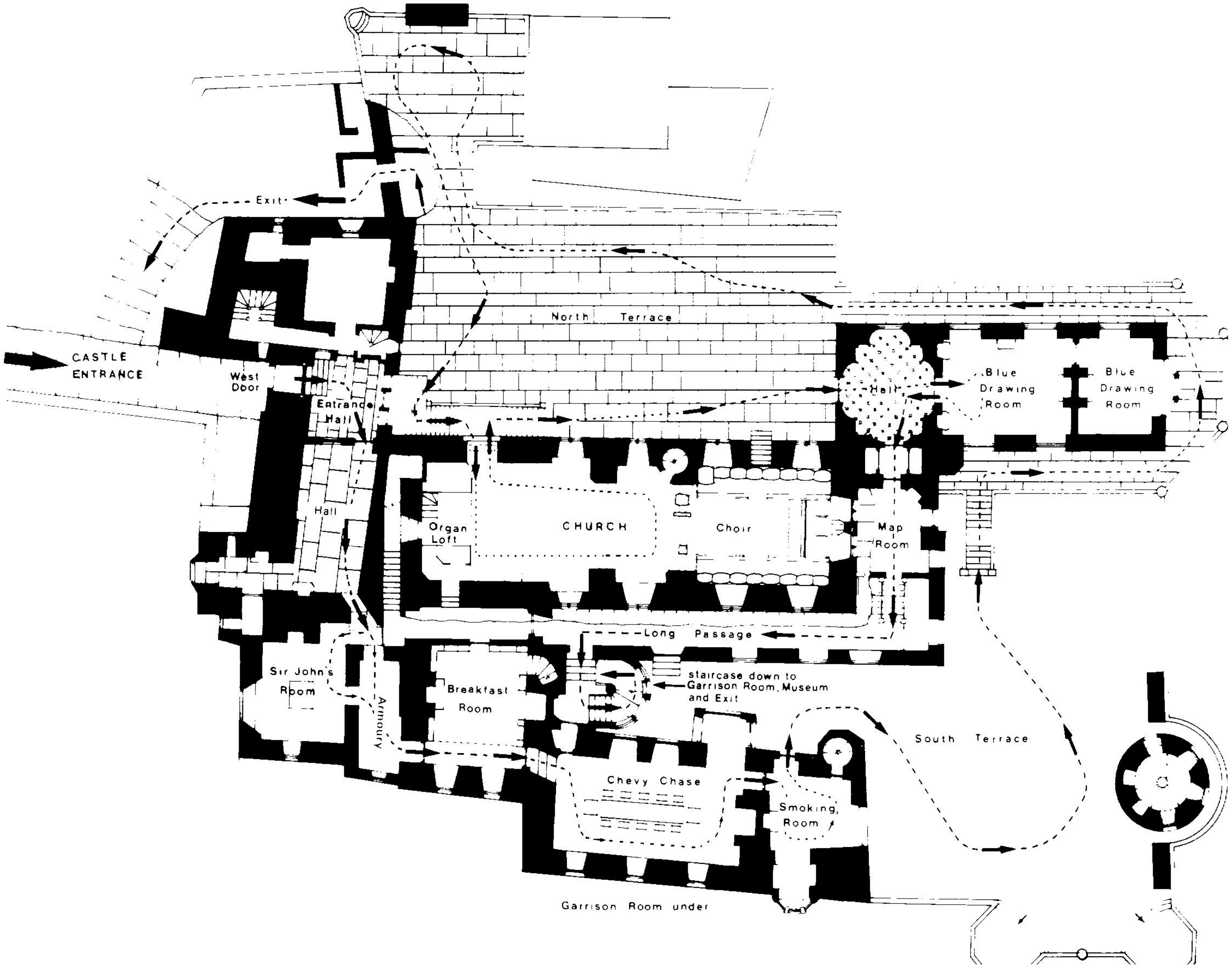
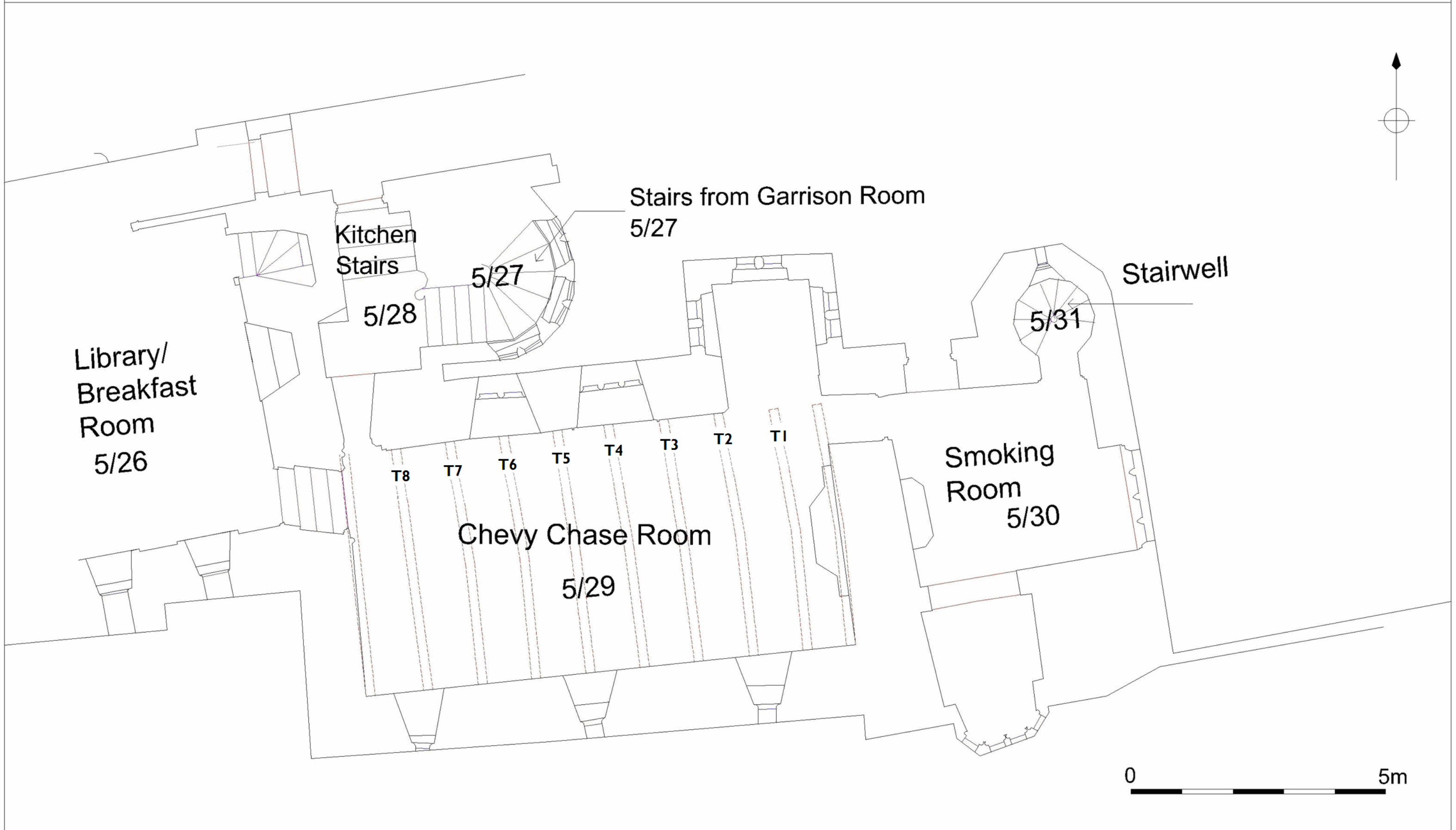


Figure 3: Site plan, reproduced from St Aubyn (1978, inside front cover)

Figure 4: Chevy Chase room, roof structure (viewed from the west)



Plan of Chevy Chase Room, St Michael's Mount, Cornwall.

Drawing supplied by MRDA Architects, London

Figure 5: Plan of Chevy Chase room, showing the truss numbering (MRDA Architects)

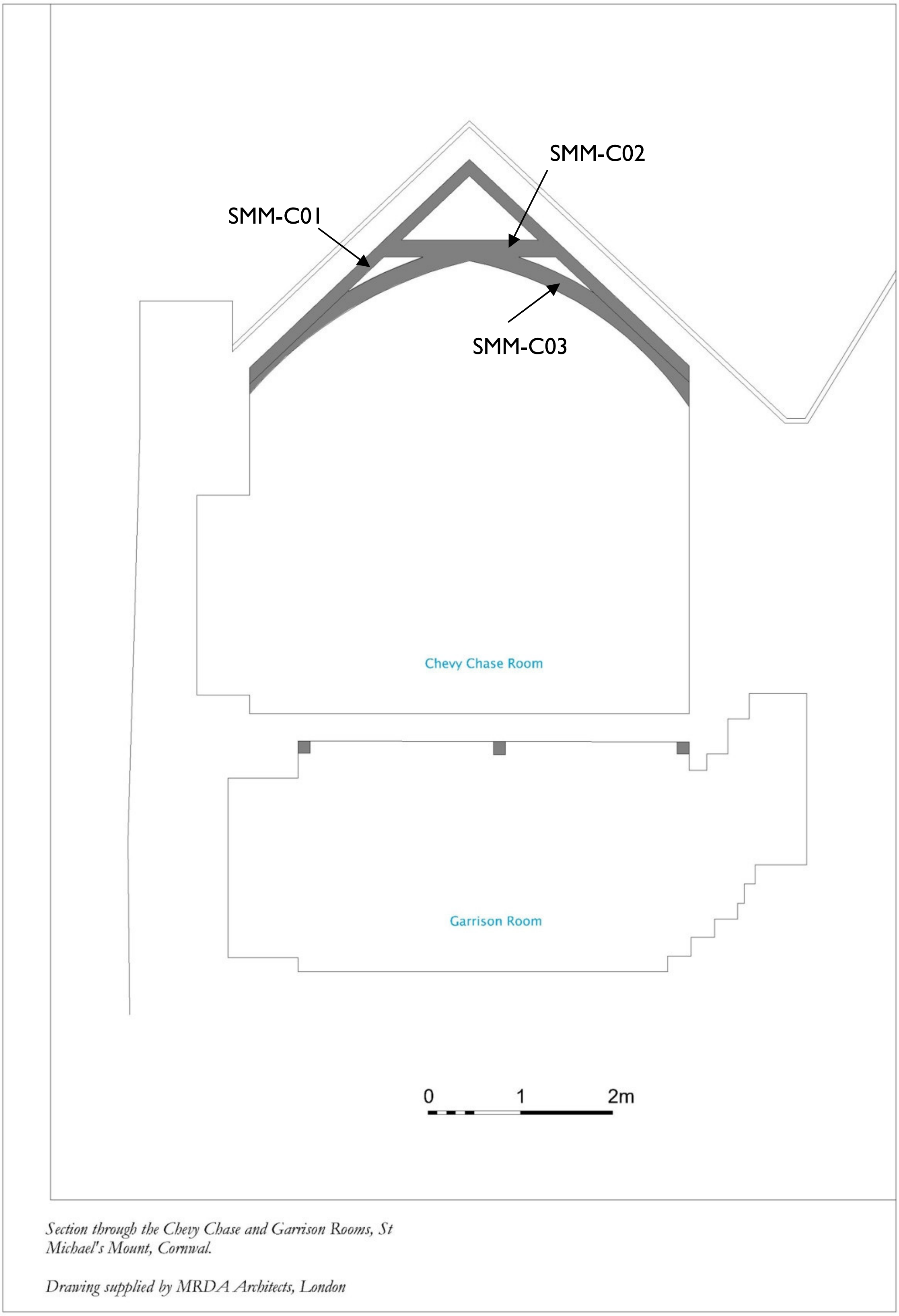


Figure 6: East facing section through truss 2, showing the location of samples SMM-C01–3 (MRDA Architects)

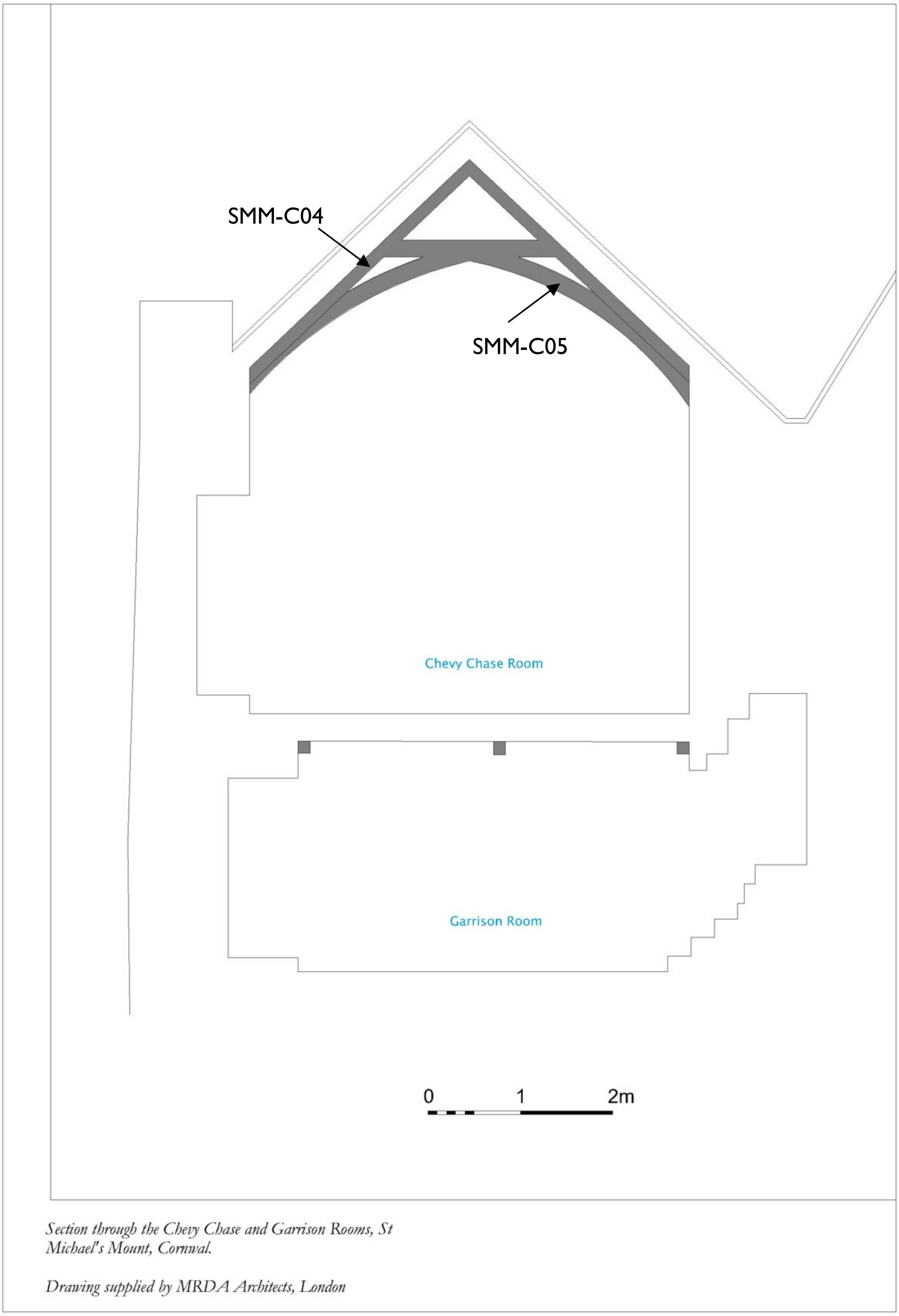


Figure 7: East facing section through truss 3, showing the location of samples SMM-C04 and SMM-C05 (MRDA Architects)

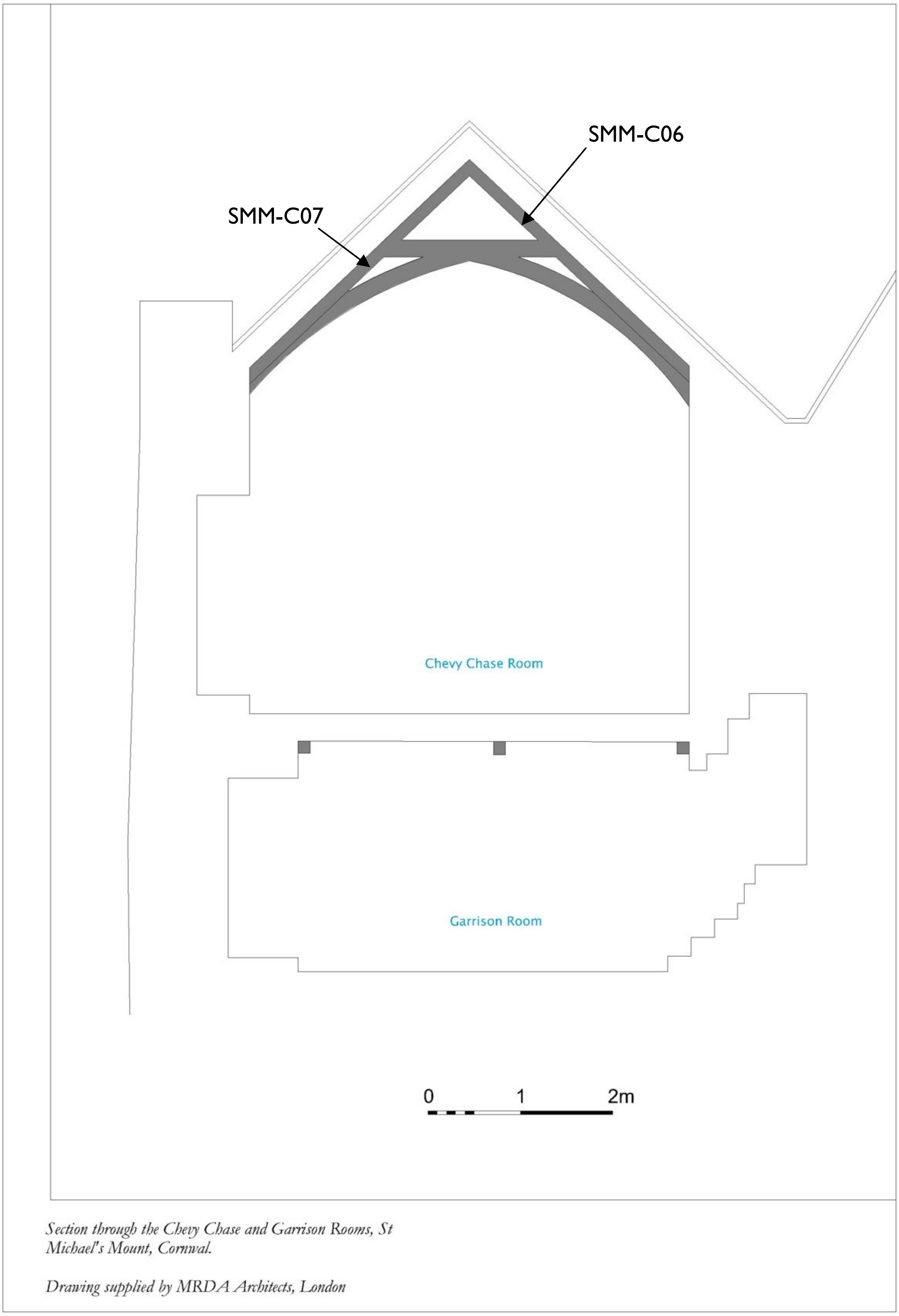


Figure 8: East facing section through truss 4, showing the location of samples SMM-C06 and SMM-C07 (MRDA Architects)

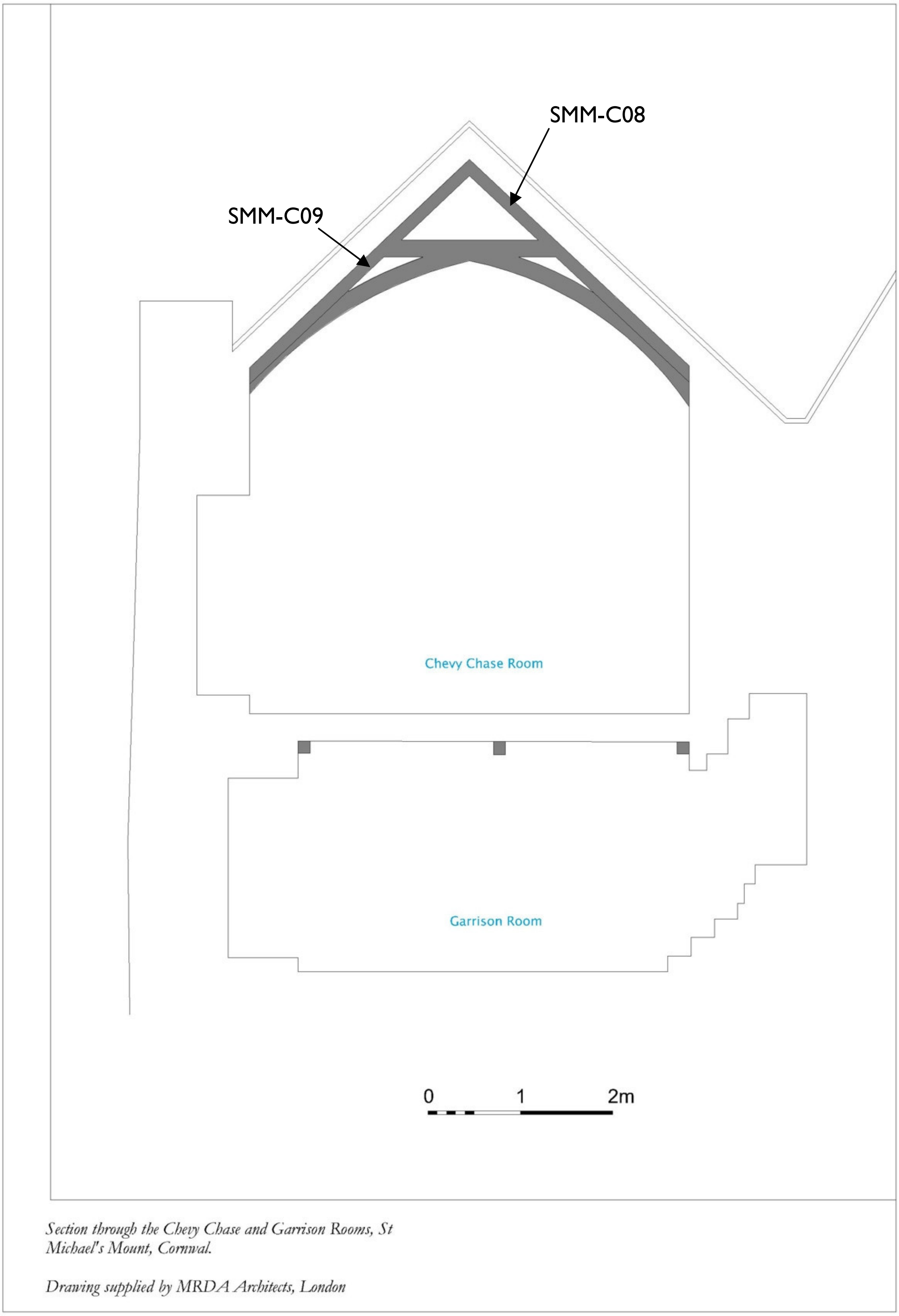


Figure 9: East facing section through truss 5, showing the location of samples SMM-C08 and SMM-C09 (MRDA Architects)

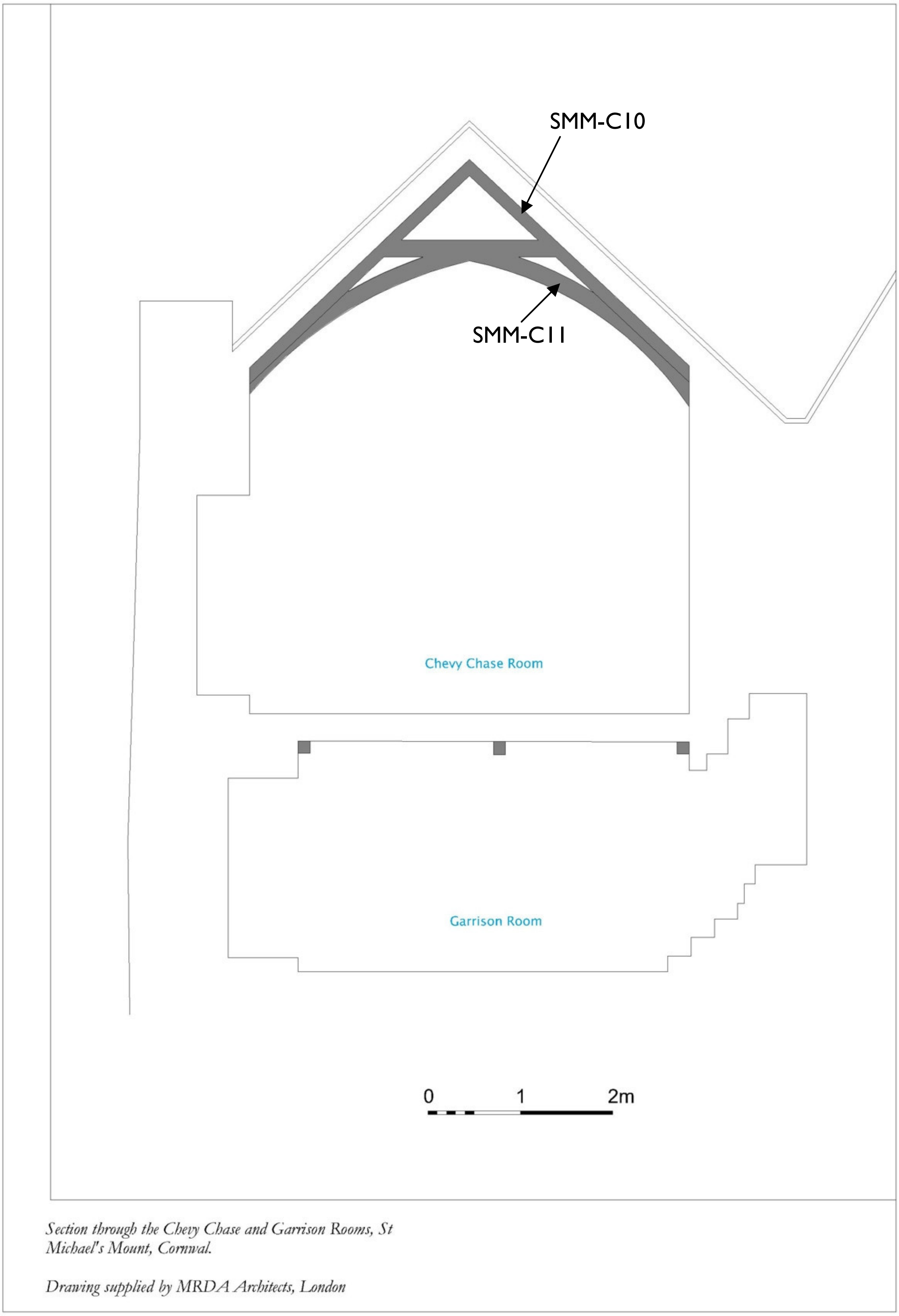


Figure 10: East facing section through truss 6, showing the location of samples SMM-C10 and SMM-C11 (MRDA Architects)

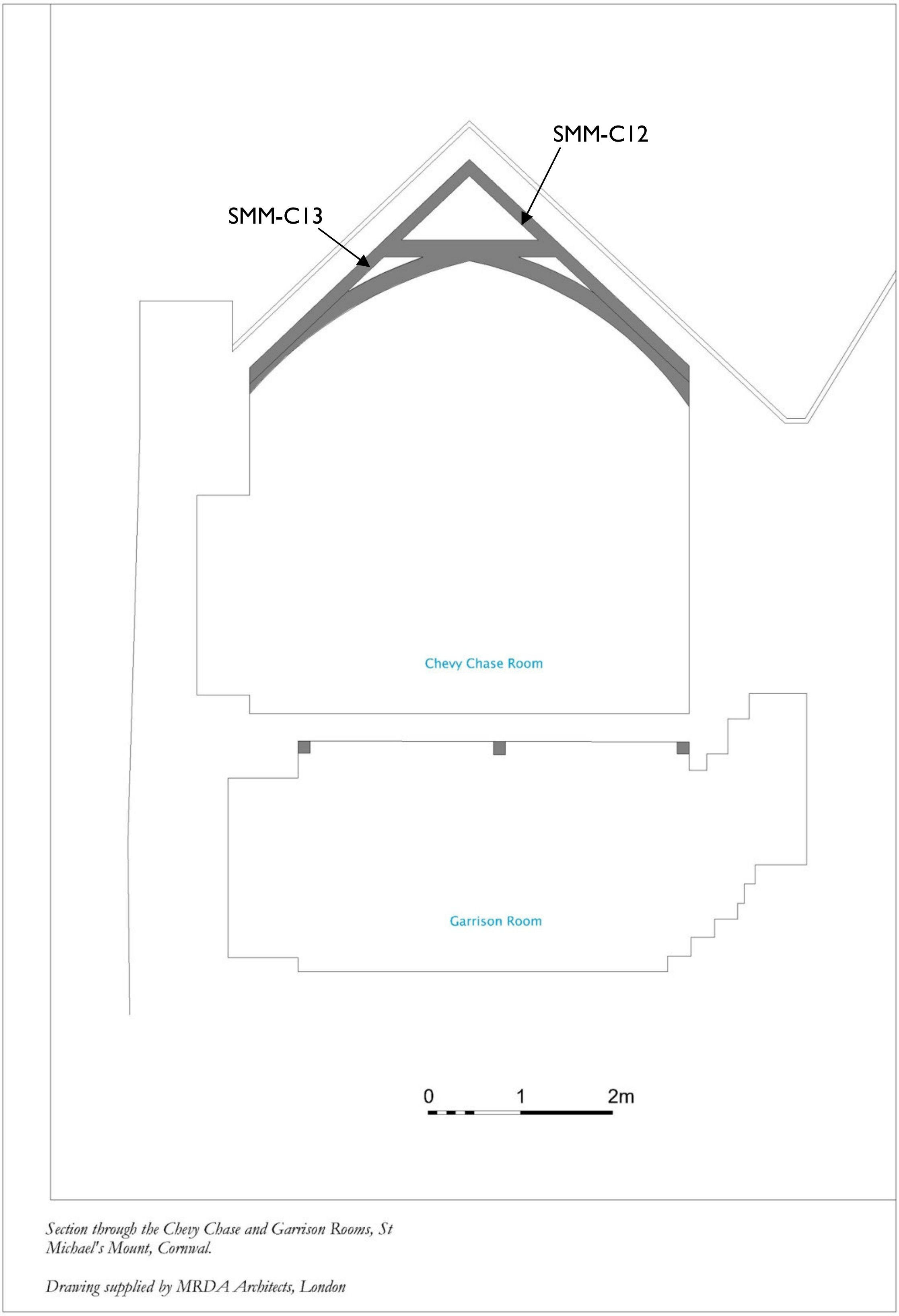


Figure 11: East facing section through truss 8, showing the location of samples SMM-C12 and SMM-C13 (MRDA Architects)

Data of measured samples – measurements in 0.01mm units

SMM-C01A 42
162 343 421 367 363 353 329 390 335 451 323 342 325 363 405 489 368 336 413 306
366 332 343 366 267 325 272 254 273 284 278 330 246 246 304 292 372 364 453 492
374 340
SMM-C01B 42
162 344 419 375 388 349 323 403 335 459 325 346 334 377 393 488 381 338 418 318
350 343 348 381 283 320 280 250 274 280 285 316 245 244 298 278 375 349 453 495
370 309
SMM-C02A 57
77 266 187 271 245 230 284 202 153 346 203 134 198 102 501 471 483 350 223 288
221 128 189 332 353 291 225 130 191 230 188 320 283 317 346 431 515 306 181 171
109 109 126 221 240 273 182 143 125 178 236 98 193 242 163 106 83
SMM-C02B 57
88 255 186 261 252 238 287 193 149 363 200 138 202 105 480 484 478 356 219 279
213 122 197 325 353 298 236 124 198 220 182 300 295 313 345 437 531 290 179 173
108 106 132 223 240 269 190 129 121 153 233 101 171 224 161 110 82
SMM-C04A 44
249 430 334 398 438 404 419 286 398 327 316 284 294 327 416 300 253 363 297 336
331 368 415 313 319 349 281 222 204 238 208 194 220 265 291 302 241 280 261 237
248 273 297 109
SMM-C04B 44
184 423 335 386 435 435 394 307 388 325 327 277 288 328 410 306 261 362 294 337
332 359 398 308 321 355 285 245 212 249 202 204 216 259 284 302 243 285 259 234
204 296 294 130
SMM-C05A 43
257 511 474 253 146 263 371 336 324 235 214 352 405 381 234 278 267 293 235 266
215 244 170 191 204 270 241 295 325 316 212 230 279 293 184 209 205 195 210 194
191 227 149
SMM-C05B 43
267 516 467 254 145 258 374 340 309 240 214 349 394 401 231 275 288 276 235 270
207 236 173 210 216 268 236 294 332 313 210 234 275 298 170 217 197 200 189 211
190 232 162
SMM-C06A 48
209 243 317 335 290 244 223 213 249 230 166 151 225 299 257 192 215 216 236 263
241 217 179 148 188 197 220 188 241 276 255 258 239 256 309 188 266 173 237 255
217 254 297 242 145 145 172 84
SMM-C06B 48
189 243 321 319 297 261 225 214 258 214 177 157 213 282 251 197 212 216 240 277
229 223 180 148 193 195 219 209 216 294 247 270 242 264 302 179 272 177 226 272
216 249 279 257 141 142 200 84
SMM-C07A 43
202 374 318 370 343 391 387 366 367 353 368 339 253 306 346 357 382 285 415 429
393 393 359 453 494 416 378 327 273 222 181 191 185 190 195 204 246 198 175 241
155 176 131
SMM-C07B 43
201 390 316 373 335 392 394 385 371 360 379 339 257 305 342 357 390 290 409 432
391 368 350 461 471 424 388 307 246 236 172 208 186 193 186 187 256 199 167 240
145 158 129
SMM-C10A 54
347 514 458 304 387 367 430 269 263 296 392 318 280 328 242 216 246 212 154 246
172 246 317 240 108 173 158 135 164 94 107 128 131 151 236 349 207 200 229 205
234 232 129 152 157 162 220 204 204 217 227 216 209 186

SMM-C10B 54
335 478 453 287 368 349 369 258 263 316 383 323 284 353 248 232 247 190 148 247
166 240 305 242 109 167 162 138 161 101 98 129 132 151 233 375 208 201 228 201
233 241 127 154 158 166 219 208 210 216 226 229 195 166
SMM-C11A 86
135 258 292 200 238 275 240 243 176 268 155 160 176 186 142 124 94 81 73 93
73 104 91 108 123 119 85 74 47 40 99 170 229 273 137 115 107 111 149 97
82 146 170 122 141 127 51 50 58 101 115 110 146 187 130 126 132 122 265 318
297 466 474 383 286 361 341 318 285 274 219 177 235 197 231 227 358 300 352 349
321 336 381 330 323 409
SMM-C11B 86
182 228 295 201 232 268 225 251 177 277 157 175 170 192 145 123 100 92 68 95
70 107 92 103 119 120 84 56 50 49 94 184 215 250 133 115 111 114 149 96
81 148 174 125 144 127 63 47 58 98 119 95 164 186 132 130 130 135 290 340
284 434 488 386 292 382 354 321 303 286 216 181 229 200 226 229 351 304 352 368
314 346 382 325 317 419
SMM-C12A 48
526 604 689 527 354 380 296 300 259 200 216 208 243 188 192 256 178 134 134 195
270 307 217 167 191 207 210 197 238 297 296 317 288 270 225 241 198 155 153 209
224 282 263 180 250 182 153 167
SMM-C12B 48
507 581 675 522 361 372 285 298 256 205 210 203 248 164 196 234 177 132 138 198
272 297 220 153 188 217 216 203 241 292 298 326 297 277 236 234 202 154 150 215
220 284 258 180 251 175 167 192

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 1 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 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 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 2 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 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.

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 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 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.

Figure 2: Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, 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.

Figure 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.

Figure 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.

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 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 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 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 5. 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 5 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 straight forward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

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

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

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

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

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

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

7. *Ring-width Indices*. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar 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

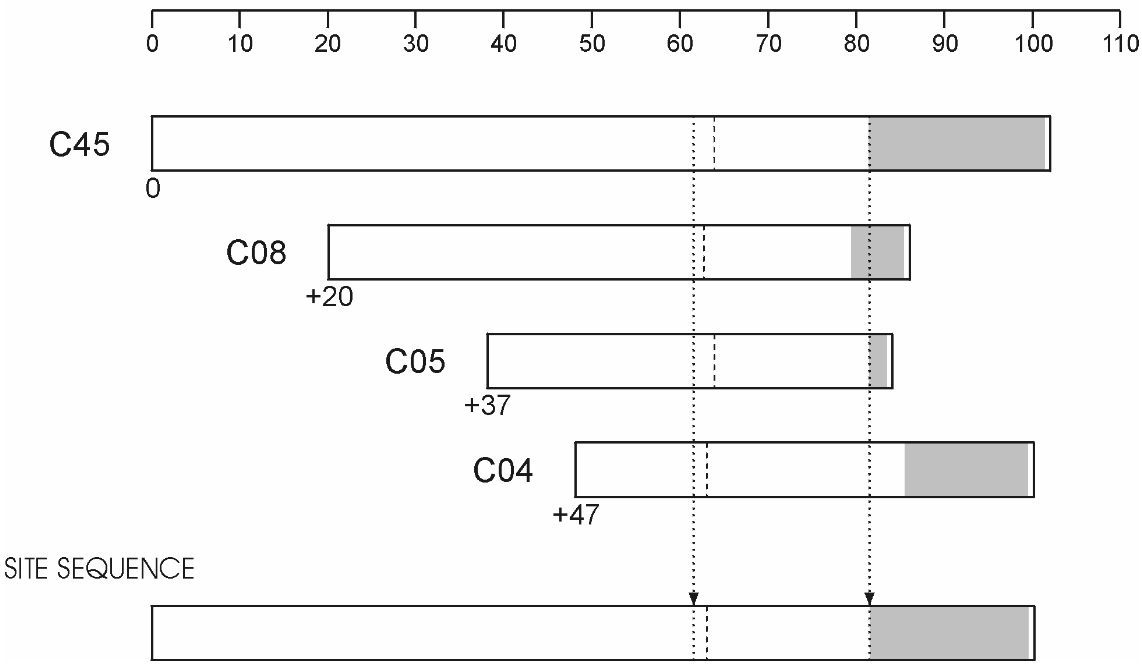


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

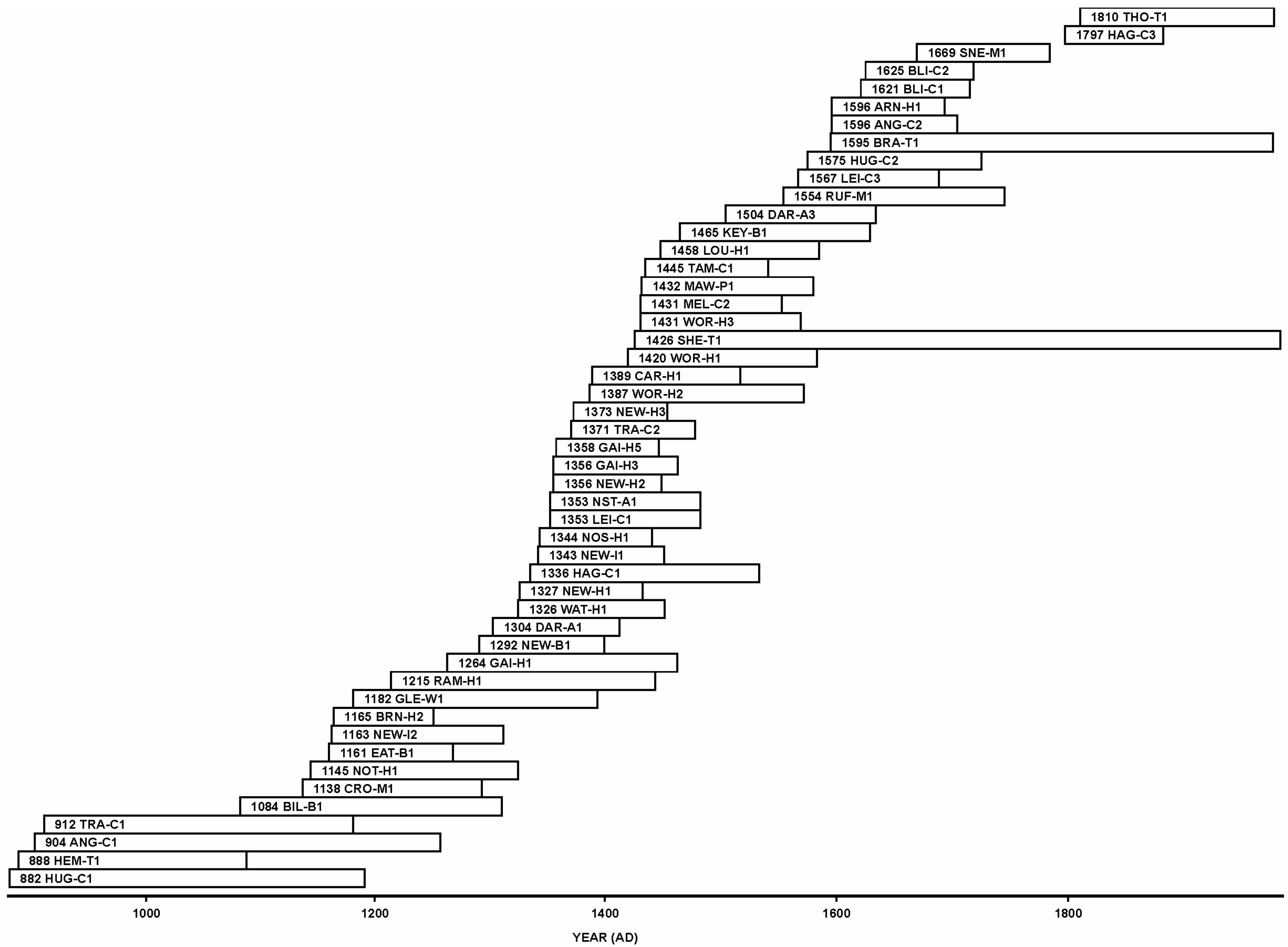
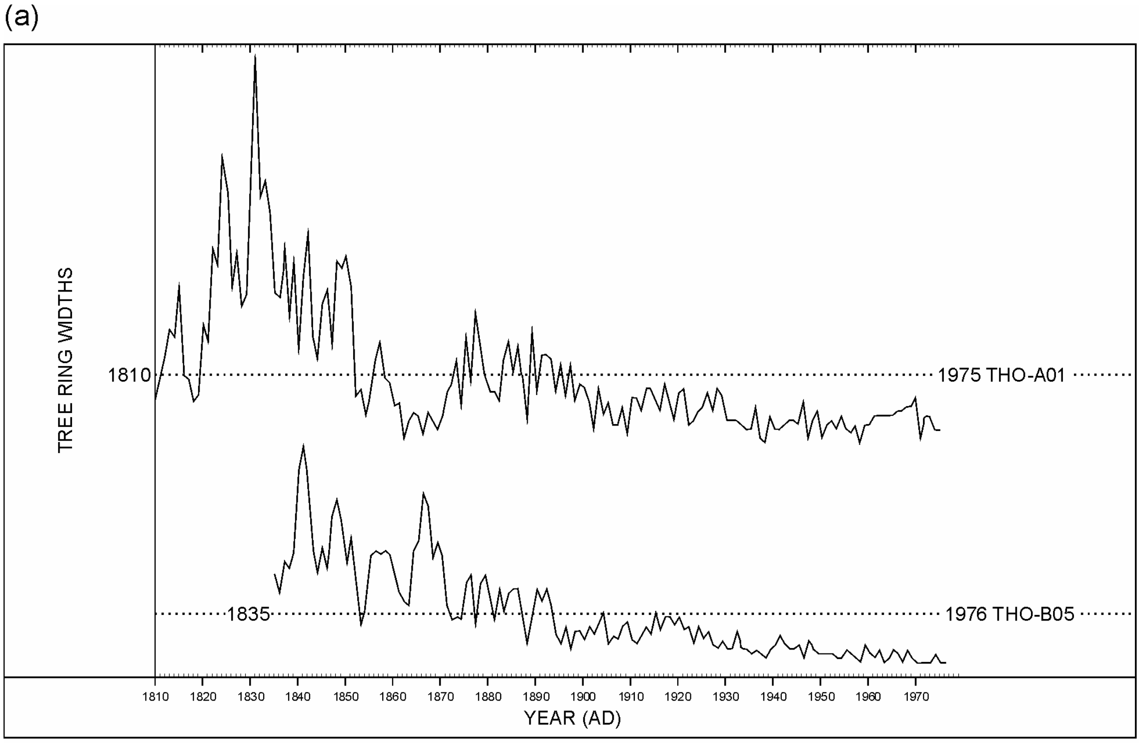


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87



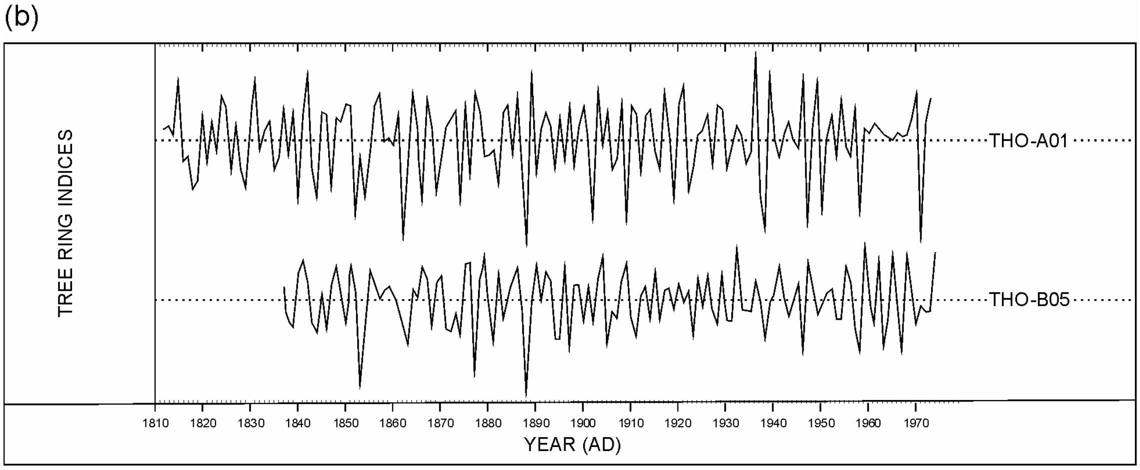


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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

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