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Summary

Analysis by dendrochronology was undertaken on samples from two window lintels at this site. There was no cross-matching between them and they could not be dated individually. It has therefore not been possible to provide tree-ring dating evidence indicating whether these two lintels relate to the original early fourteenth-century construction of the Tower, or a later phase of modification or repair.Subsequently a series of eight contiguous decadal samples from one of the lintels (WKWA01) was submitted for radiocarbon dating by Accelerator Mass Spectrometry. Analysis of these results by wiggle-matching suggests that this timber was felled in the early-fourteenth century and is a survival from the primary phase of construction.

Keywords

Dendrochronology
Standing Building
Radiocarbon Dating

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Introduction

Warkworth Castle lies on a high point at the neck of a loop in the River Coquet, at the south end of the main street through the town (NU 247 057, Fig 1). Warkworth itself is set within the loop of the river and developed along with the castle as one of the planned boroughs of the Middle Ages. The Castle, the home of the Percy family, includes the early twelfth-century motte and bailey, the mid twelfth- to sixteenth-century tower keep castle, and the fourteenth-century church. The whole is surrounded by a deep and impressive ditch.

The walls and structures within the castle site show evidence of many phases of reconstruction and modification. For example, apart from some mid twelfth-century masonry, the earliest surviving remains are found along the south curtain wall and in the south-west corner. These include the early thirteenth-century gatehouse with its projecting semi-octagonal bays at the front, a recess for a drawbridge, and a portcullis. Of similar date is Carrickfergus Tower set to the south end of the west wall, while the solar shows evidence for fourteenth-century reconstruction. In the late-fourteenth or early-fifteenth century, towers were built at the south-east and north-east corners of the Hall. A view of the castle is shown in Figure 2.

The castle also includes an extensive array of ancillary buildings including halls, towers, stable-blocks, kitchens, and storage areas. Amongst these others structures is the projecting semi-octagonal Grey Mare's Tail Tower on the east wall, which is thought to have been built *c* AD 1300. The interior resembles Carrickfergus Tower. In the sixteenth century this was used as a gaol and contains wall carvings that may have been made by prisoners. A view of the tower is provided in Figure 3.

The castle became part of the chain of defences against the Scots along with Bamburgh and Alnwick. Warkworth was besieged twice by the Scots in AD 1327 but on both occasions the defences held. In AD 1332 the castle passed from the Clavering family to the Percy family. The castle became a favourite residence of the Percys but in AD 1405 it was besieged and taken by Henry IV when the 3rd Percy, Lord of Warkworth, was involved in Archbishop Scrope's rebellion against the king.

Sampling

Sampling and analysis by tree-ring dating of timbers within Grey Mare's Tail Tower were commissioned by English Heritage, and undertaken by the Nottingham University Tree-ring Dating Laboratory. Although it was believed that there might be timbers binding the walls of the tower, there were none and the only samples available consisted of lintels to three narrow slit-windows at first-floor level. The purpose of this analysis was to inform a new English Heritage guidebook.

Unfortunately core samples could only be obtained from two of these lintels, the third being behind an iron grill set within the stonework and therefore inaccessible. Each sample was given the code WKW-A (for Warkworth, site 'A') and numbered 01 and 02. The positions of the sampled timbers within the Tower are given in Figure 4, with a photograph of the windows being given in Figure 5. Details of the samples are given in Table 1.

Tree-ring Analysis

The two samples obtained were prepared by sanding and polishing and their annual growth-ring widths were measured. The data of these measurements are given at the end of this report. These data were then compared to each other by the Litton/Zainodin grouping procedure (see appendix). Unfortunately there was no cross-matching between them. Each sample was then compared individually to a large number of reference chronologies for oak. There was, however, no conclusive cross-matching and both samples must remain undated.

Radiocarbon Sampling and Analysis

Following the failure of the tree-ring analysis to produce dating evidence, one of the dendrochronology cores (WKW-A01) was cut into eight contiguous blocks, each containing wood of ten-year's growth. All eight samples were dated by Accelerator Mass Spectrometry at the Scottish Universities Environmental Research Centre (SUERC), East Kilbride. They were prepared using methods outlined in Hoper *et al* (1998), and measured as described by Xu *et al* (2004).

The results are conventional radiocarbon ages (Stuiver and Polach 1977; Table 2), and are quoted in accordance with the international standard known as the Trondheim convention (Stuiver and Kra 1986). Duplicate results have been quoted for each decadal block. In each case the results are statistically consistent, and so a weighted mean of the duplicate measurements has been taken before calibration and further analysis (Ward and Wilson 1978).

The SUERC laboratory maintains a continual programme of quality assurance procedures, in addition to participation in international inter-comparisons (Scott 2003). These tests indicate no laboratory offsets and demonstrate the validity of the precision quoted. In addition to the duplicate measurements on each sample from Warkworth, extended counting time was also applied to each graphite target because of the precision required for this application.

Calibration

The calibrations of these results, relating the radiocarbon measurements directly to calendar dates, have been calculated using the calibration curve of Reimer *et al* (2004) and the computer program OxCal (v3.10) (Bronk Ramsey 1995; 1998; 2001). The calibrated date ranges for each sample given in Table 2 have been calculated using the maximum intercept method (Stuiver and Reimer 1986). They are quoted in the form recommended by Mook (1986), with the end points rounded outwards to 5 years. The graphical distributions of the calibrated dates, given in outline in Figures 7-8 and 12, are derived from the probability method (Stuiver and Reimer 1993).

Wiggle-matching

Wiggle-matching is the process of matching a series of radiocarbon determinations, which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of different blocks of wood submitted for dating is known precisely by counting the rings in the timber.

Radiocarbon wiggle-matching of tree-ring sequences that cannot be absolutely dated through dendrochronology is not new (eg Clarke and Renfrew 1972; Clarke and Morgan 1983; Baillie 1995, 69-70), although until now it has been confined largely to assemblages of waterlogged wood (eg van der Plicht *et al* 1995; Bayliss and Pryor 2001; Bayliss *et al* 2003; Kromer *et al* 2001). This is because large samples of wood were required for high-precision radiocarbon dating by Liquid Scintillation Spectrometry or Gas Proportional Counting. Recent advances in the accuracy and precision of radiocarbon measurements produced by Accelerator Mass Spectrometry (eg Bronk Ramsey *et al* 2004; Dellinger *et al* 2004), however, now make this approach feasible for small wood samples, such as those available from cores taken for tree-ring dating. An excellent summary of the history and variety of approaches employed for wiggle-matching is provided by Galimberti *et al* (2004).

A variety of the wiggle-matching approach has also been applied to validate, or choose between, different matching positions of a floating tree-ring sequence against the absolutely dated master chronologies (Bayliss *et al* 1999). This is useful in situations where possible cross-matching positions have been identified by the tree-ring analysis, but where these are not strong enough statistically to be accepted without independent, confirmatory, evidence.

The 'least-squares' Method

The first approach used to fit the radiocarbon measurements from core WKW-A01 to the radiocarbon calibration curve places the core in a position that minimises the differences between the radiocarbon results from the core and those forming the calibration curve. This method is described by Pearson (1986).

At Warkworth, we know that the mid-point of each wood sample submitted for radiocarbon dating is 10 years earlier or later than the next sample in the sequence, and that the outermost sample had lost 3-4 rings in coring from the heartwood/sapwood boundary. Consequently, the heartwood/sapwood boundary falls nine years after the date provided by the wiggle-matching, and an allowance for the missing sapwood rings has to be added to this to provide an estimated date for the felling of the actual timber.

This approach has been applied using a non-distributed version of the computer program CAL25 (van der Plicht 1993). The specific algorithm implemented is described in Bronk Ramsey *et al* (2001).

The least-squares 'best fit' for this sequence against the calibration curve indicates a mean date for core WKW-A01 is AD 1290 (Fig 6). The result is in accordance with the simple calibrated date range of cal AD 1275 – 1295 (95% confidence) for the same sample.

This method, however, only provides a single date and with no estimate of error, unlike the Bayesian approach described below.

A Bayesian Approach

A second method of wiggle-matching has been applied to these data, using a Bayesian approach to combine the radiocarbon dates with the relative dating provided by the tree-ring analysis. This is a probabilistic approach, which determines which parts of the calibrated radiocarbon date are most likely given the tree-ring evidence. This results in a reduced date range, known as a *posterior density estimate*, which is shown in black in Figures 7-8 and 12, and given in italics in the text. A general introduction to the Bayesian approach to interpreting archaeological data is provided by Buck *et al* (1996). The approach to wiggle-matching adopted here is described by Christen and Litton (1995).

The technique used is a form of Markov Chain Monte Carlo sampling, and has been applied using the program OxCal v3.10 (http://www.rlaha.ox.ac.uk/orau/), which uses a mixture of the Metropolis-Hastings algorithm and the more specific Gibbs sampler (Gilks *et al* 1996; Gelfand and Smith 1990). Details of the algorithms employed by this program are available from the on-line manual or in Bronk Ramsey (1995; 1998; 2001). The algorithms used in the models described below can be derived from the structure shown in Figures 7, 8, and 12.

The chronological model for the dating of sample WKW-A01 is shown in Figure 7. This includes the weighted mean of the replicate radiocarbon measurements on each of the decadal blocks of wood from the core, the information that the centre ring of block 8 is 10 years earlier than the centre ring of block 7 etc, and the information that after the centre point of block 1 there were 9 years to the heartwood/sapwood boundary of the timber. In addition, the probability distribution of the number of sapwood rings expected to be missing from the sample has been applied to the result of the wiggle-match to provide an estimate of the date of felling of the timber. The methodology for this approach is described by Bayliss and Tyers (2004).

This analysis suggests that timber WKW-A01 was felled in *cal AD 1290 – 1340 (95% probability; barkEdge*; Fig 7), or *cal AD 1295 – 1320 (68% probability)*. However, this model has poor overall agreement ($A_{overall}$ = 31.7%; Bronk Ramsey 1995). This means that the radiocarbon measurements are not in accord with the tree-ring sequence of the timber samples. Further inspection suggests that this poor agreement is entirely caused by the poor individual agreement of block 7 (A=6.1%), which is rather earlier than expected from its position in the sequence.

For this reason, the analysis was repeated with the earlier radiocarbon measurement from block 7 (SUERC-6564; Table 1) excluded. This model, shown in Figure 9, has good overall agreement ($A_{overall}$=66.6%), although the remaining measurement from block 7 (SUERC-6563; Table 1) still has relatively poor individual agreement (A=26.2%). This analysis provides a slightly modified estimated date for the felling of timber WKW-A01 of *cal AD 1295 – 1340 (95% probability; barkEdge*; Fig 9), or *cal AD 1295 – 1320 (68% probability)*.

The least-squares method gave a wiggle-match result for core WKW-A01 at AD 1290 (χ^2 fit value=2.95). This date corresponds with the *95% probability* derived for the same sample using the Bayesian methodology (*cal AD 1275 – 1290*), lying at the later end of the range.

To test the sensitivity of this analysis in relation to the calibration data, the model shown in Figure 8 was re-calculated using the older calibration dataset of Stuiver *et al* (1998). The model has poor overall agreement ($A_{overall}$=53.7%), with SUERC-6563 and block 8 both showing poor individual agreement indices (A=33.4% and A=32.1%). This analysis suggests that timber WKW-A01 was felled in cal *AD 1300 – 1345 (95% probability)* or *1305 – 1330 (68% probability)*. Inspection of the calibration data covering the period of the Warkworth core (Fig 9) shows that the data points between AD 1234 and AD 1214 have a considerably larger spread than subsequent data points in the later thirteenth-century. This may contribute to the poor agreement of the earlier blocks in this core (Fig 10). It is instructive that better agreement is achieved by the currently internationally-agreed calibration curve, which adopts a more sophisticated approach to the estimation of the errors on the curve (Buck and Blackwell 2004). This exercise suggests that our estimate of the felling date of this timber may vary by up to a decade as radiocarbon calibration data are refined.

A comparison of the Bayesian and least-squares method show similar results, however the dates do not overlap. While the least-squares method has determined a heartwood/sapwood boundary date of AD 1299, the Bayesian model estimates this date too be *cal AD 1275 – 1295* (*95% probability*; *heartSap*; Fig 8).

Interpretation

The combined results of the radiocarbon dating and tree-ring analysis presented above provide an estimated felling date for WKW-A01 of *cal AD 1295 – 1340 (95% probability;*

barkEdge; Fig 8), or *cal AD 1295 – 1320 (68% probability)*.

This date must now be considered in relationship to what is known about the ownership of the Castle from historical sources. In the late-thirteenth century Warkworth Castle was in the ownership of Robert Fitz Roger (AD 1247 – 1310), who acceded to the estate in *c* AD 1265. He was summoned to parliament as a baron by writ on 28th June AD 1283. King Edward I visited the Castle on 18th December AD 1292. On 11th September AD 1297 Robert Fitz Roger and his son, John Fitz Robert (AD 1266 – 1332), were taken prisoner at the Battle of Stirling. John Fitz Robert was summoned to parliament as John de Clavering in AD 1299. On 29th March AD 1310 he paid homage for the estate, on the death of his father (Hodgson 1899; 27-30).

John appears to have been in severe financial difficulties. On 20th November AD 1311 he received substantial grants of property from the King, agreeing in return to surrender his lands should he fail to produce a male heir. However, on the 1st May AD 1317 he acknowledged a debt for £600 to Fredulcius Hubertini, a merchant of Lucca (ibid, 30), and on 1st March AD 1328, Henry Percy, the second Lord Percy (AD 1310-52), was assigned reversion of the estates of the Clavering family in Northumberland (Northumberland; 154-5). These included the castle and barony of Warkworth. On 23 January AD 1332 the lands reverted to Henry Percy, on the death of John Fitz Robert (*Cal Close*; 390-1).

In architectural terms, the *posterior density estimate* produced by the scientific dating of the lintel in Grey Mare's Tail Tower ties in very neatly with Edward I's building campaign at Berwick-upon-Tweed, which began in AD 1296 (Fig 11). It is probable that the Warkworth tower follows the royal works. If so, Grey Mare's Tail Tower was probably built by Robert Fitz Roger between AD 1296 and his death in AD 1310. It is likely that John Fitz Robert's debts would have prevented building works, more or less from the moment of his accession to the estates. This consideration aside, following the Battle of Bannockburn on 24th June 1314, building on the border practically came to a complete halt for a decade. The alternative is that Henry Percy built the Grey Mare's Tail Tower after AD 1332.

Examination of the *posterior density estimate* for the date of the lintel from the tower (Fig 8), suggests that the probability that this timber was felled after AD 1332 is only 8.4%. Therefore, it is unlikely that Henry Percy constructed the tower. The probability that the timber was felled before AD 1296 is only 0.8%, so it is even less likely that the construction of the tower preceded the King's works at Berwick-upon-Tweed. Another chronological model, which combines the historical evidence for the construction of the tower before AD 1310 with the scientific dating evidence, is shown in Figure 12. The model shows good overall agreement ($A_{overall}$ = 60.4%), which suggests that the scientific data are in accord with the historical evidence that financial constraints would have prevented the construction of the tower after AD 1310.

The model shown in Figure 13, which combines all the scientific and historical evidence, suggests that Grey Mare's Tail Tower was constructed in *cal AD 1295 – 1315 (95% probability; barkEdge*; Fig 12), or *cal AD 1300 – 1310 (68% probability)*.

Conclusions

Analysis by dendrochronology was undertaken of samples from two window lintels at this site. There was no cross-matching between them and they could not be dated individually, thus no dendrochronological dating evidence has been provided for the Grey Mare's Tail Tower. The dating of so few samples is often difficult, particularly in the absence of intra-site cross-matching when it is necessary to attempt to date each sample individually.

A series of 16 radiocarbon measurements from core WKW-A01 were undertaken once tree-ring analysis had failed to produce absolute dating. Wiggle-matching of these results against the currently internationally-agreed calibration data set (Reimer *et al* 2004), suggests that this timber was felled in *cal AD 1295 – 1340 (95% probability; barkEdge*; Fig 8), or *cal AD 1295 – 1320 (68% probability)*. Consequently, it appears that at least one of the lintels from Grey Mare's Tail Tower is a survival from the original construction.

Further modelling, combining the scientific data with historical evidence, suggests that the Tower was constructed in *cal AD 1295 – 1315 (95% probability; barkEdge*; Fig 12), or *cal AD 1300 – 1310 (68% probability)*.

Acknowledgements

We would like thank Professor Marian Scott, of the Department of Statistics, Glasgow University, and the staff of the Scottish Universities Environmental Research Centre Radiocarbon and AMS Laboratories for their input into bringing such a challenging application to a successful conclusion.

Table 1: Details of samples from Grey Mare's Tail Tower, Warkworth Castle, Nr Alnwick, Northumberland

Sample Number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
WKW-A01	Lintel to east window	106	h/s	------	------	------
WKW-A02	Lintel to south window	104	h/s	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample

Table 2: Radiocarbon determinations from contiguous 10-year blocks of core WKW-A01 from Grey Mare's Tail Tower, Warkworth Castle. Replicate radiocarbon measurements have been combined prior to calibration following the method in Ward and Wilson (1978)

Laboratory Number	**Sample ID**	**Material**	**$\delta^{13}C$ (‰)**	**Radiocarbon Age (BP)**	**Calibrated Date (95% confidence)**	***Posterior Density Estimate (95% probability)(see Fig 9)***
SUERC-6540	WKW-A01 Block 1	*Quercus* spp.	-25.1	700 ± 20		
SUERC-6541	WKW-A01 Block 1	*Quercus* spp.	-25.3	695 ± 20		
mean	T'=0.0; v=1, T'(5%)=3.8			698 ± 14	cal AD 1275 – 1295	*cal AD 1275 – 1290*
SUERC-6542	WKW-A01 Block 2	*Quercus* spp.	-24.8	715 ± 20		
SUERC-6543	WKW-A01 Block 2	*Quercus* spp.	-24.4	710 ± 20		
mean	T'=0.0, v=1, T'(5%)=3.8			713 ± 14	cal AD 1270 – 1290	*cal AD 1265 – 1280*
SUERC-6547	WKW-A01 Block 3	*Quercus* spp.	-24.0	760 ± 20		
SUERC-6548	WKW-A01 Block 3	*Quercus* spp.	-24.7	765 ± 20		
mean	T'=0.0, v=1, T'(5%)=3.8			763 ± 14	cal AD 1250 – 1280	*cal AD 1255 – 1270*
SUERC-6550	WKW-A01 Block 4	*Quercus* spp.	-26.0	775 ± 20		
SUERC-6551	WKW-A01 Block 4	*Quercus* spp.	-25.4	790 ± 20		
mean	T'=0.3, v=1, T'(5%)=3.8			783 ± 14	cal AD 1220 – 1275	*cal AD 1245 – 1260*
SUERC-6556	WKW-A01 Block 5	*Quercus* spp.	-25.8	800 ± 20		
SUERC-6557	WKW-A01 Block 5	*Quercus* spp.	-25.9	810 ± 20		
mean	T'=0.1, v=1, T'(5%)=3.8			805 ± 14	cal AD 1210 – 1265	*cal AD 1235 – 1250*
SUERC-6558	WKW-A01 Block 6	*Quercus* spp.	-24.2	810 ± 20		
SUERC-6559	WKW-A01 Block 6	*Quercus* spp.	-24.4	810 ± 20		
mean	T'=0.0, v=1, T'(5%)=3.8			810 ± 14	cal AD 1210 – 1265	*cal AD 1225 – 1240*
SUERC-6563	WKW-A01 Block 7	*Quercus* spp.	-24.3	850 ± 20		*cal AD 1215 – 1230*
SUERC-6564	WKW-A01 Block 7	*Quercus* spp.	-24.4	880 ± 20		
mean	T'=1.1, v=1, T'(5%)=3.8			865 ± 14	cal AD 1155 – 1220	
SUERC-6566	WKW-A01 Block 8	*Quercus* spp.	-24.4	850 ± 20		
SUERC-6567	WKW-A01 Block 8	*Quercus* spp.	-24.4	870 ± 20		
mean	T'=0.5, v=1, T'(5%)=3.8			860 ± 14	cal AD 1155 – 1220	*cal AD 1205 - 1220*

Figure 1: Map showing the location of Warkworth Castle, Northumberland, and Grey Mare’s Tail Tower

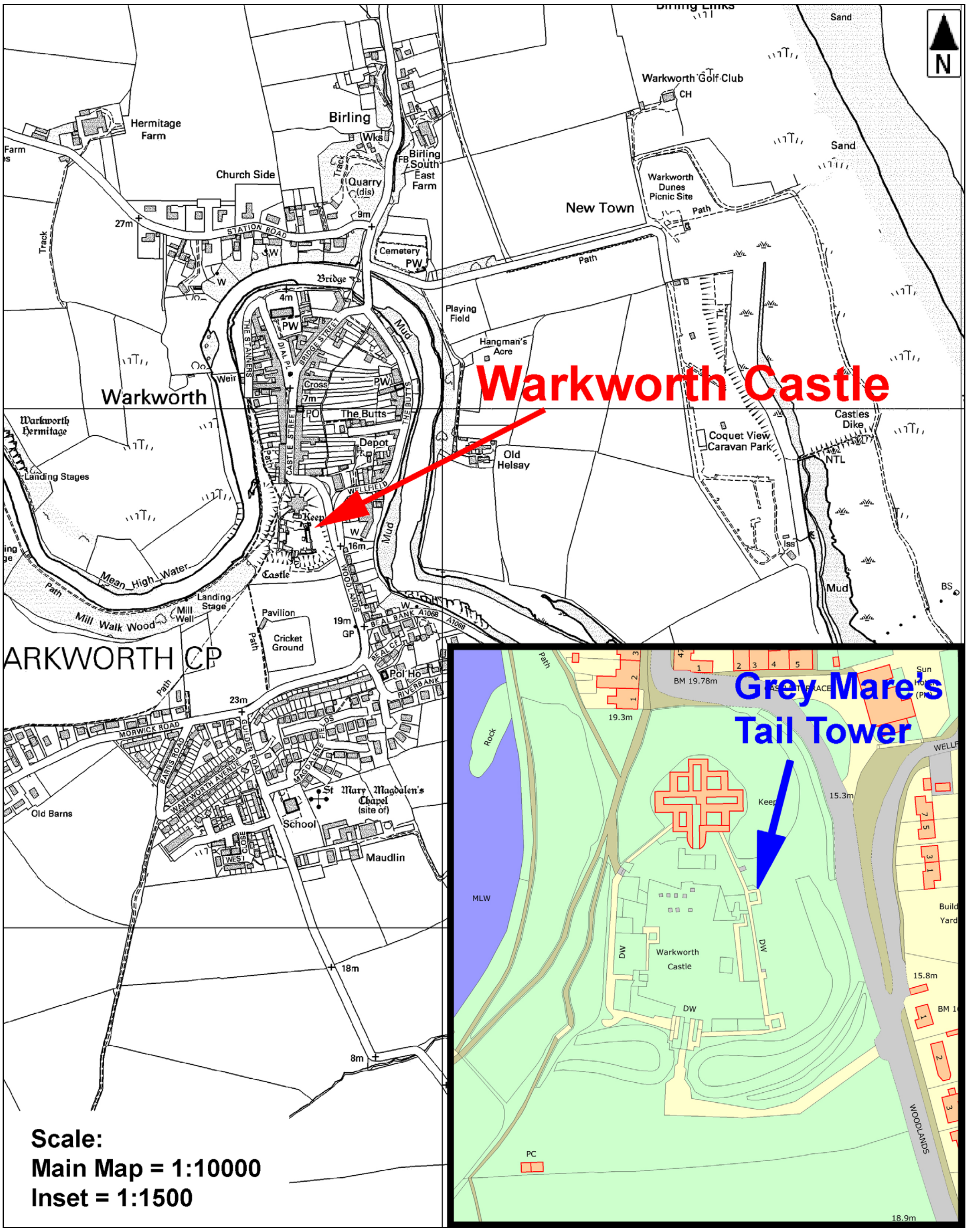


Figure 2: External view of Grey Mare's Tail Tower, Warkworth Castle (R Howard)

Figure 3: Grey Mare's Tail Tower, view from the Keep (John Goodall)

Figure 4: Plan showing the location of samples from Grey Mare’s Tail Tower

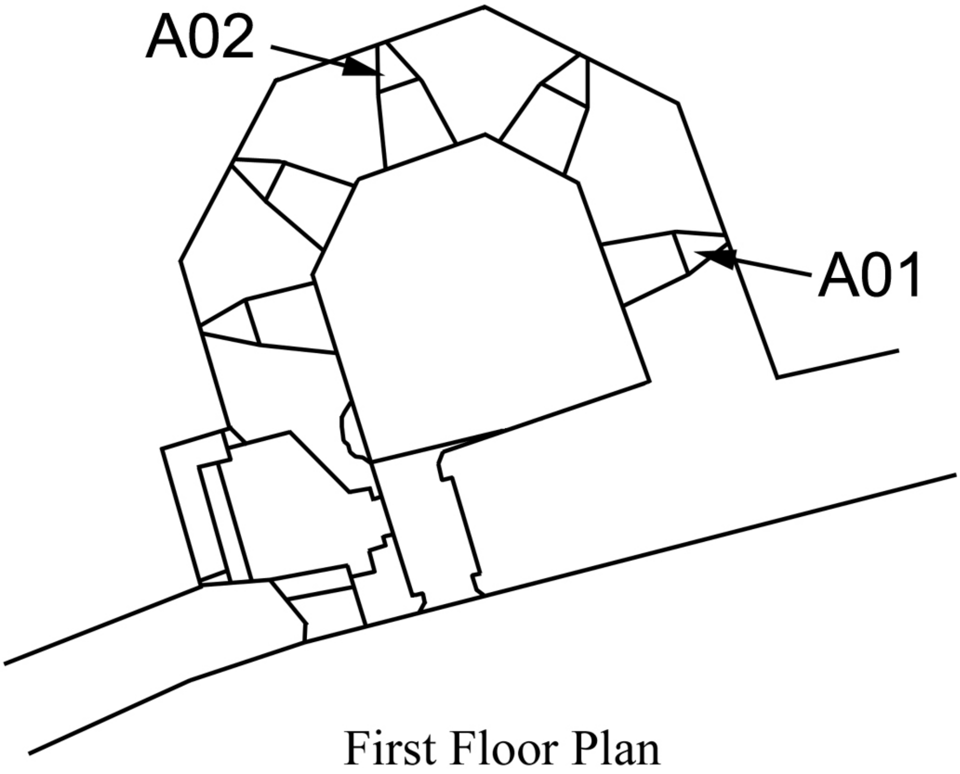


Figure 5: View of the slit windows with one of the accessible lintels (John Goodall)

Figure 6: Least-squares wiggle-match, which provides a date for the mean of WKW-A01 Block 1 of AD 1290

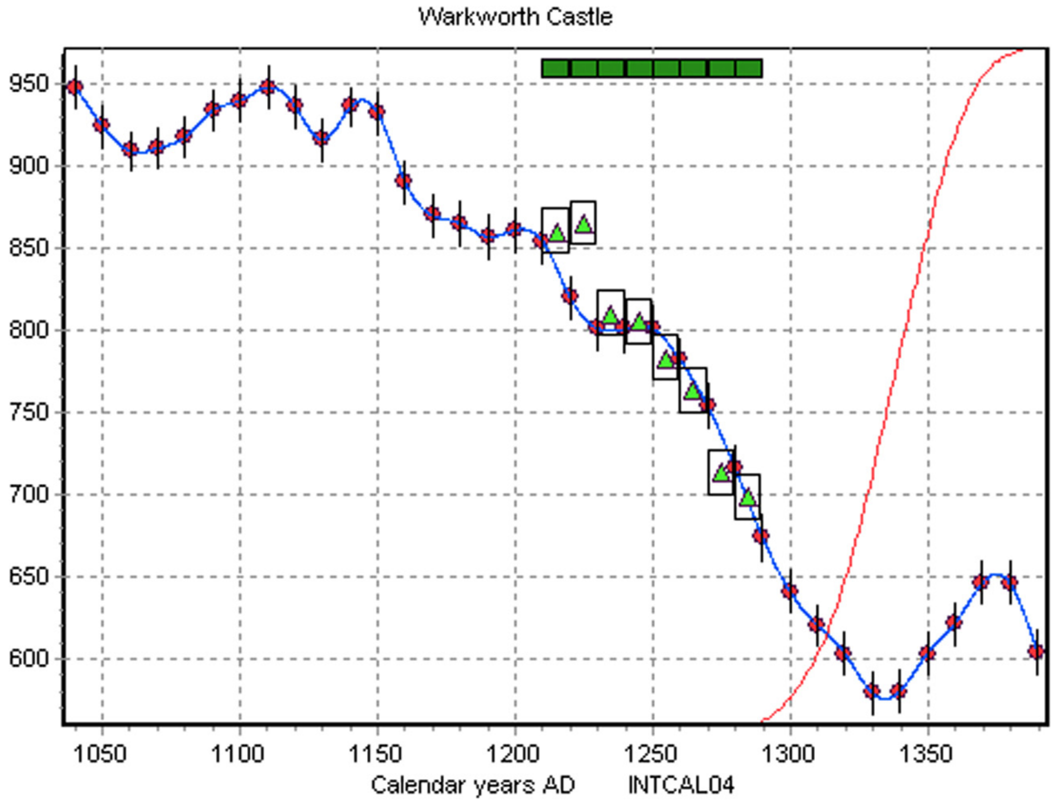


Figure 7: Probability distributions of dates from core WKW-A01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution '*barkEdge*' is the estimated date when the timber was felled. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

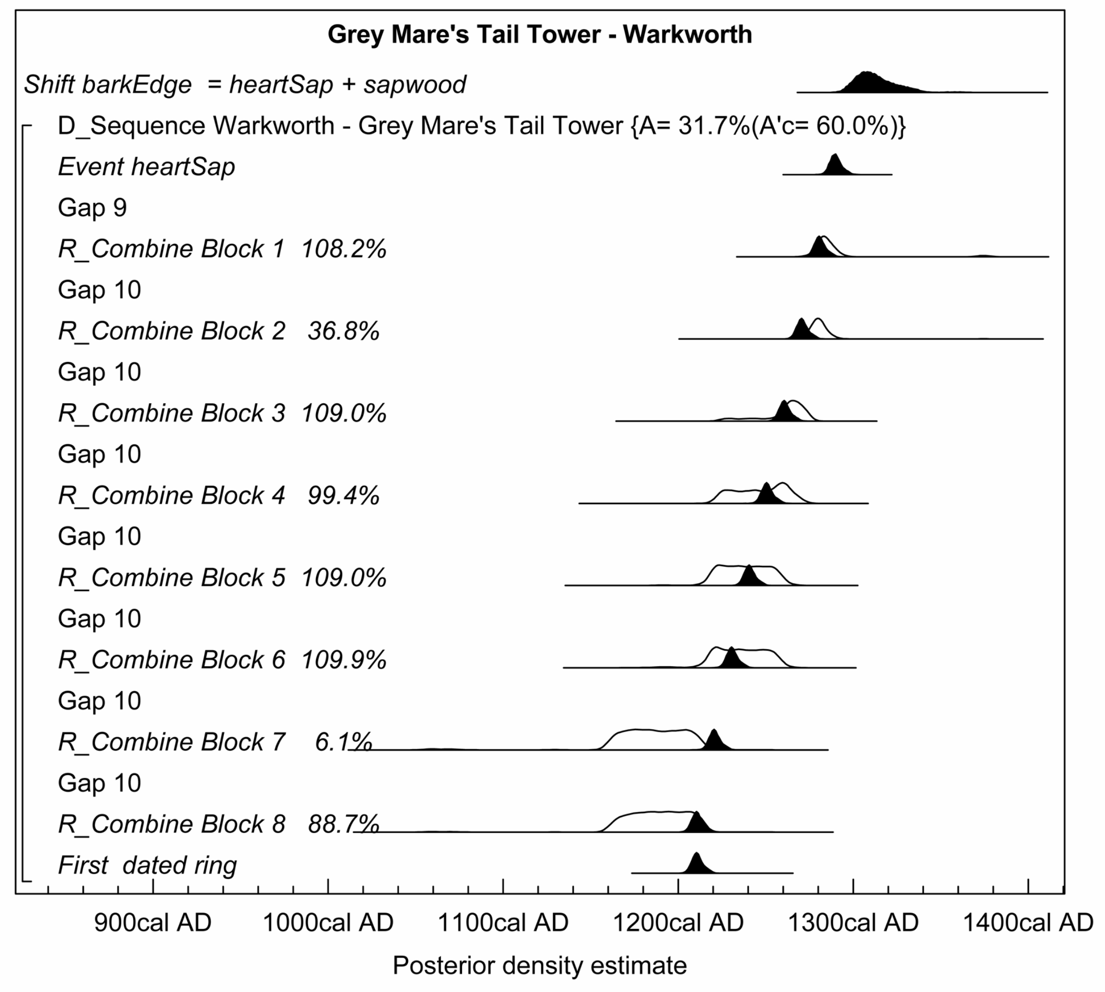


Figure 8: Probability distributions of dates from WKW-A01, with the format being identical to Figure 7. Block 7 has had one questionably old measurement removed, leaving only SUERC-6563 in its place. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

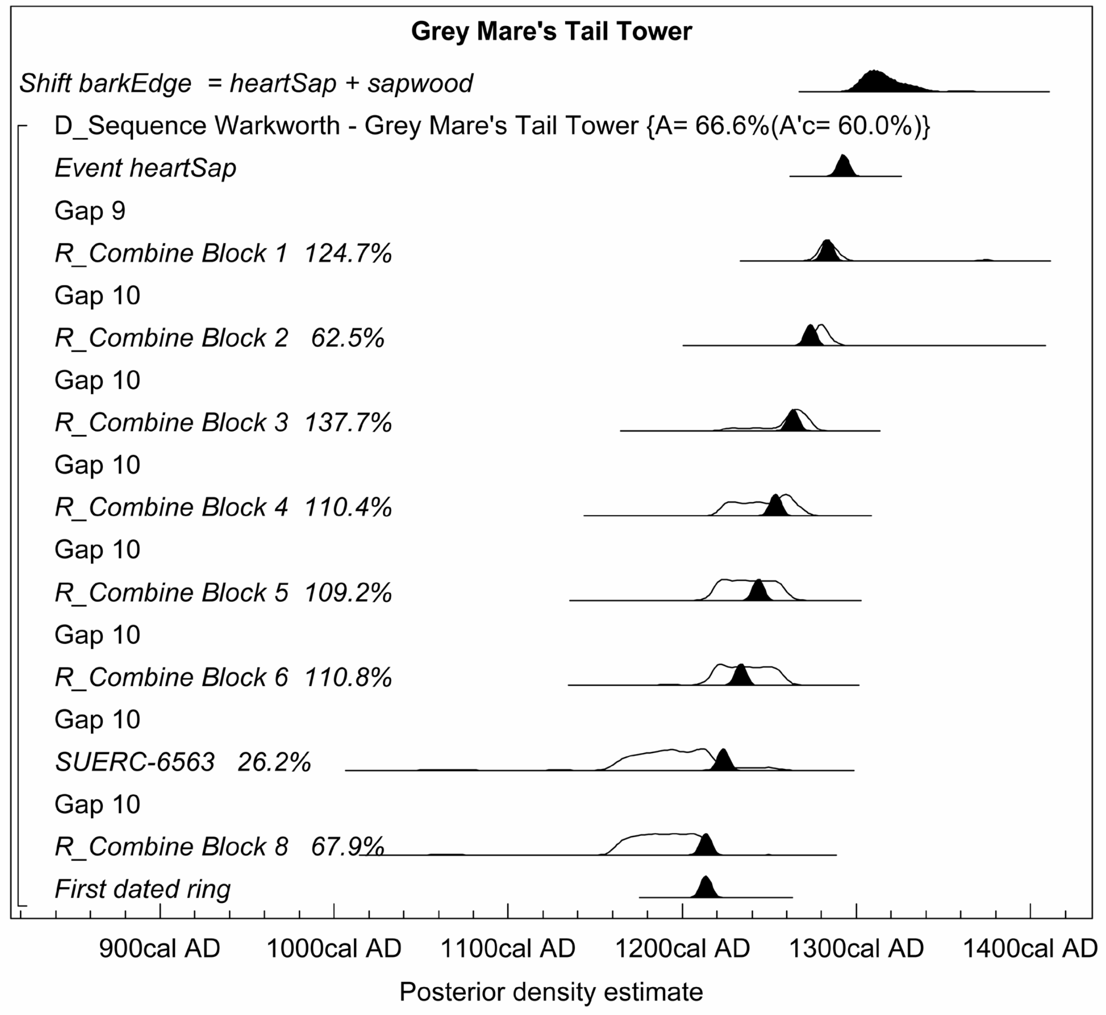


Figure 9: Graphical representation showing the data-points and their 1σ errors in the INTCAL04 radiocarbon calibration curve dataset

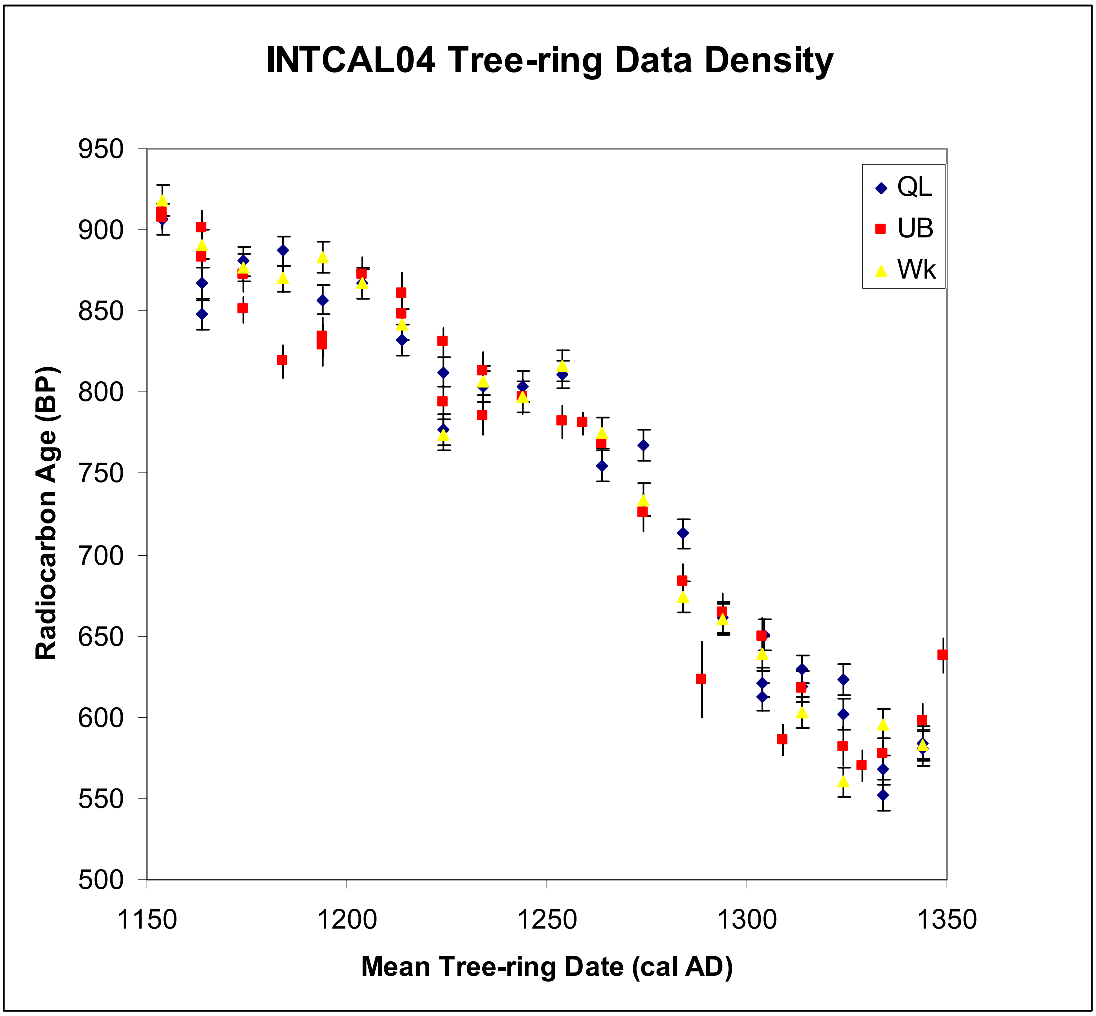


Figure 10: Graphical representation of the wiggle-matched radiocarbon measurements from WKW-A01 with their 1- and 2-σ errors plotted as boxes

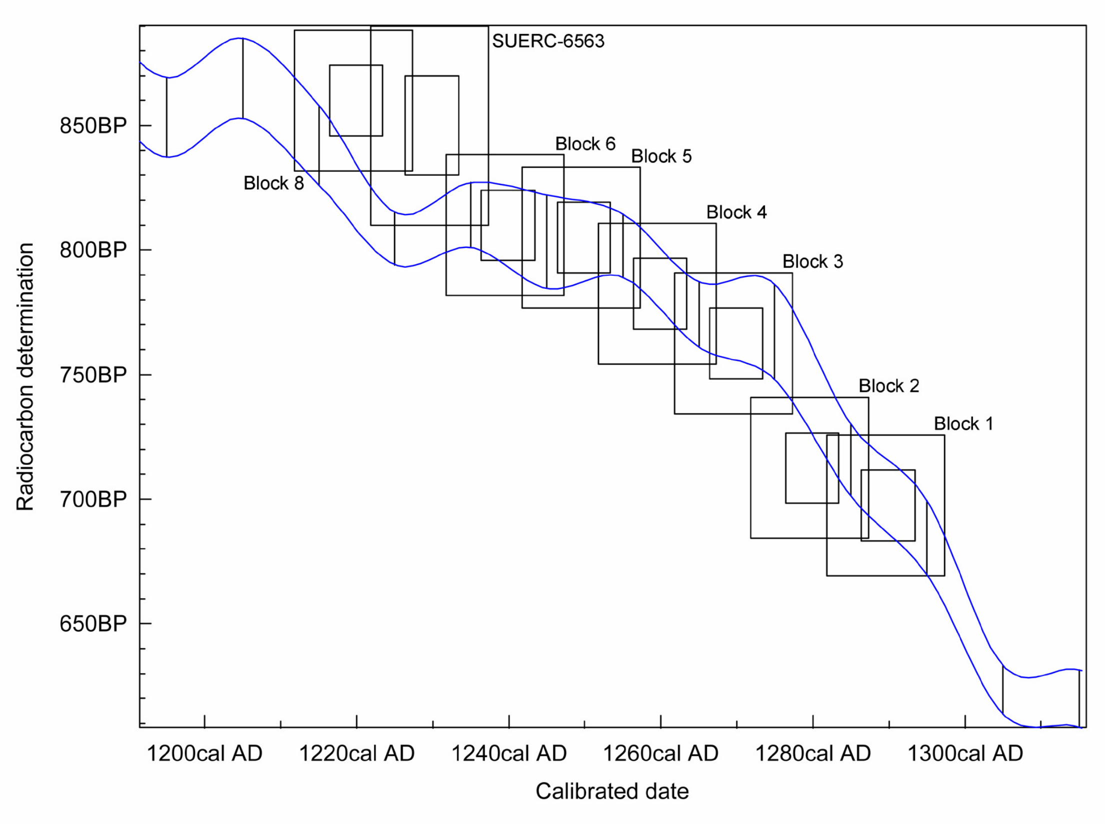
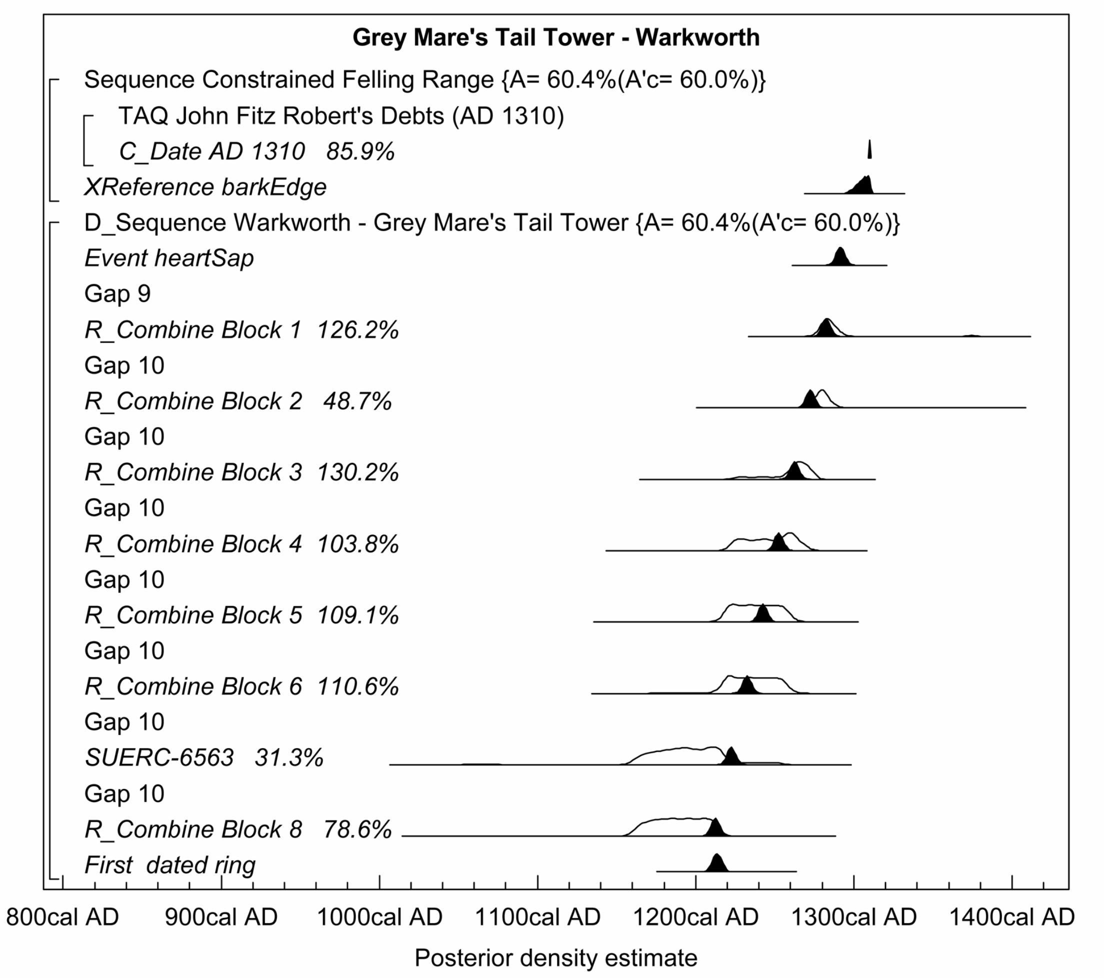


Figure 11: The remains of the Constable's Tower at Berwick -upon-Tweed, begun in AD 1296. Like the Grey Mare's Tail Tower at Warkworth, this is laid out on a polygonal plan with a deep sloping plinth and has arrow loops with splayed bases. All these features are also found in the *c* AD 1200 gatehouse and Carrickfergus Tower at Warkworth, but Berwick Castle is a much more likely source for the Grey Mare's Tail Tower and illustrates their continued popularity in the royal works nearly a century later. (John Goodall)

Figure 12: Probability distributions of dates from WKW-A01, with the format being identical to Figure 7. Block 7 has had one questionably old measurement removed, leaving only SUERC-6563 in its place. An additional sequence has been added at the top, which shows the *barkEdge* probability constrained by addition of the calendar date AD 1310, the year that the debt-ridden John Fitz Robert inherited the estate. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly



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Tree-ring Data

WKW-A01A 106
192 112 215 182 273 221 171 225 157 188 201 147 205 201 87 57 60 47 34 61 68 72 99 76 127
120 95 107 122 93 165 231 114 177 153 166 177 94 220 228 143 128 228 225 226 215 212 196 67
34 38 33 40 43 59 79 56 55 82 86 68 53 56 33 39 76 81 62 119 107 109 116 99 85 93 102
150 163 63 104 129 119 139 167 189 226 206 177 135 183 175 223 201 288 286 262 209 188 205 319
222 184 221 223 177 199

WKW-A01B 106
179 99 218 187 268 198 172 223 155 191 227 147 206 199 69 58 57 61 35 65 67 74 88 92 111
131 103 87 140 120 124 222 103 189 156 183 152 109 214 232 145 133 220 217 238 213 217 207 78
36 34 28 41 63 41 74 56 47 89 75 92 54 41 46 43 73 77 70 114 103 119 108 101 84 89 109
142 153 83 91 132 142 139 166 192 229 197 176 141 167 179 217 199 288 286 258 223 165 216 328
237 169 237 202 189 182

WKW-A02A 78
133 240 184 146 134 128 116 149 250 231 289 314 240 225 160 116 201 158 157 225 239 176 160 151
185 232 245 267 209 218 138 146 207 249 197 181 193 196 136 220 276 252 230 283 344 242 214 180
150 130 140 131 122 70 54 54 51 56 61 78 153 102 106 101 110 94 63 64 69 98 109 129 85 98
62 58 60 62

WKW-A02B 70
153 144 191 179 120 166 188 156 164 217 253 207 190 200 145 130 109 98 89 93 89 111 97 106 90
122 191 123 120 89 116 109 84 70 72 111 119 155 84 106 69 76 79 56 46 44 36 38 40 48 50
38 46 41 46 74 41 73 41 60 52 40 50 36 37 45 39 55 38 58

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 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 measure 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.

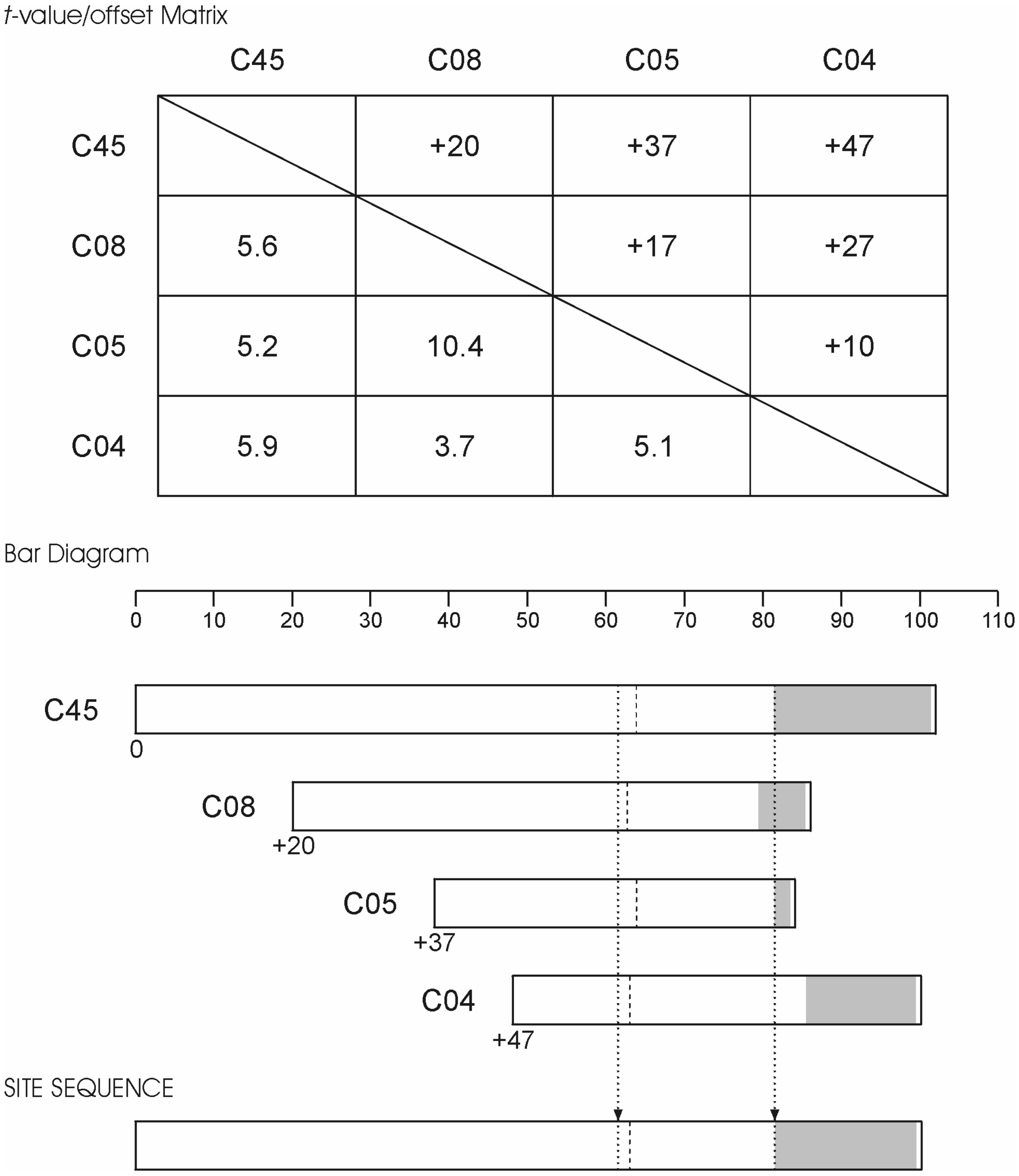
Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring 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 phenomena 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.



	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	

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.

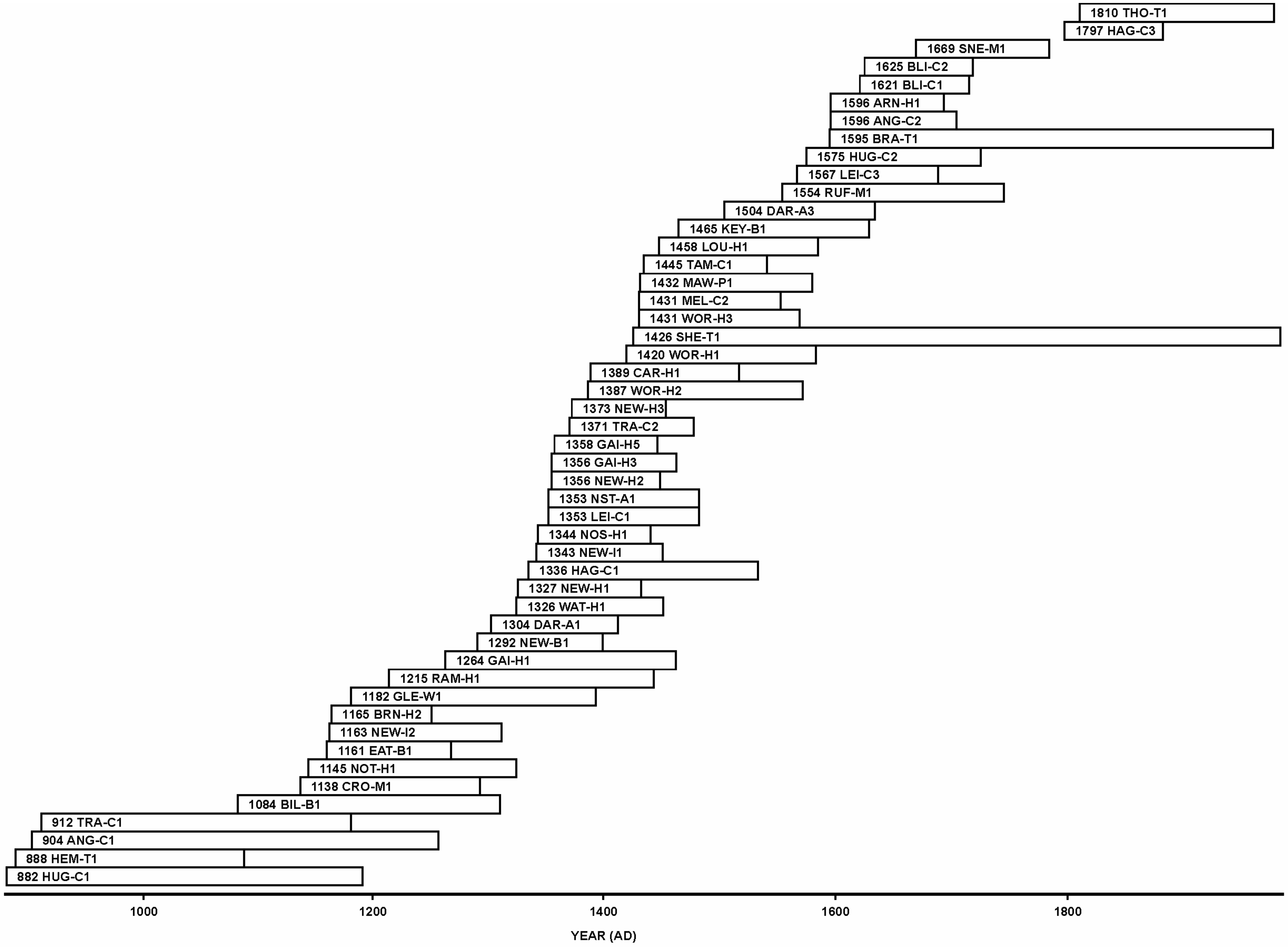


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

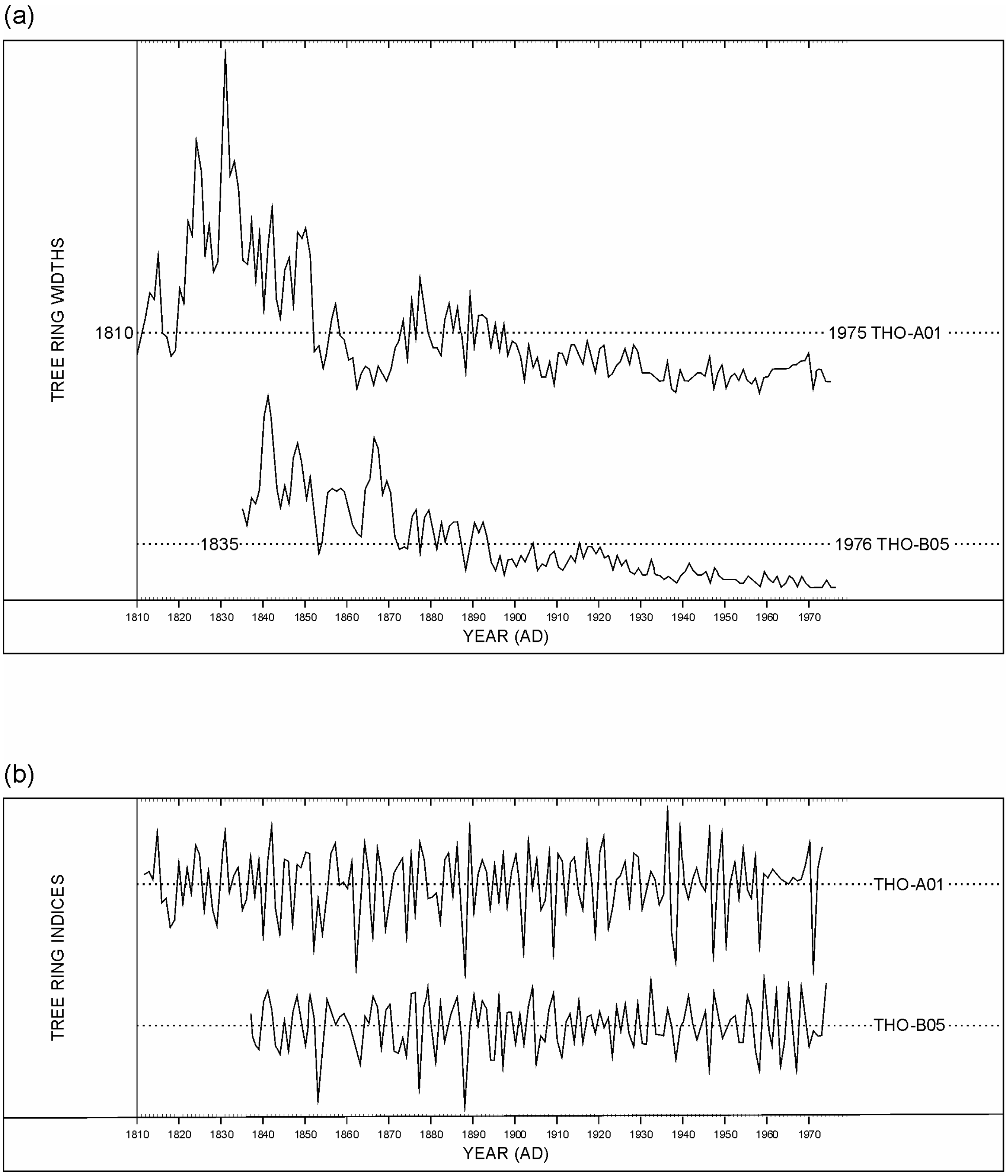


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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