WIGGLE-MATCHING USING KNOWN-AGE PINE FROM JERMYN STREET, LONDON

Cathy Tyers 1 • Jane Sidell 2,3 • Johannes van der Plicht 4 • Peter Marshall 5 • Gordon Cook 6 • Christopher Bronk Ramsey 7 • Alex Bayliss 2

ABSTRACT. A slice of pine from the period covered by single-year calibration data (Stuiver 1993) was selected to serve as part of the quality assurance procedures of the English Heritage radiocarbon dating program, following successful wiggle-matching of 14C measurements from structural 15th century English oak timbers (Hamilton et al. 2007). The timber selected was a roofing element from a house on Jermyn Street, central London, demonstrated by dendrochronology to have been felled in AD 1670. Eighteen single-ring samples were dated by the 14C laboratories at Groningen, Oxford, and SUERC: each laboratory was sent a random selection of 6 samples. This approach was intended to mimic the mix of samples and relative ages incorporated into Bayesian chronological models during routine project research. This paper presents the results of this study.

INTRODUCTION

The building at 107 Jermyn Street, London (Figure 1) formed part of a terrace of townhouses thought to be the first phase of urban settlement in this area, which is situated to the west of the earlier medieval and Roman settlements in London. Jermyn Street was part of London’s fashionable designed townscape known as the West End. Documentary evidence suggests that Jermyn Street was planned and the individual buildings erected in the 1660s and 1670s. Number 107 was a 5-storied brick building, with timber floors, framing, and roof structure, exclusively composed of Scots pine (Pinus sylvestris [L.]), retaining surprising amounts of early fabric considering its age and conversion from a townhouse to a shop in the 19th century.

The dating of imported conifer is an increasingly important aspect of dendrochronological research being developed for post-medieval building analysis in the UK. Dating of standing buildings constructed from the more usual oak is a well-developed discipline (English Heritage 1998); however, dating buildings constructed from conifer is still somewhat in its infancy (Groves 2000). Therefore, with its impending demolition, 107 Jermyn Street provided a valuable resource for extensive dendrochronological sampling. Fifty-one slices were analyzed (Groves and Locatelli 2005) with dendrochronology identifying and providing precise felling dates for 4 distinct phases of construction or modification (see Figure 2). Twenty-three of the 51 samples, forming 5 groups (Groves and Locatelli 2005: Tables 2–5), were dated by comparison with reference chronologies from Norway eastwards to the shores of the White Sea, indicating different sources for the timbers in the different groups (Groves and Locatelli 2005: Tables 11–12).

In addition to the extensive program of dendrochronology funded by English Heritage, a large-scale program of radiocarbon dating is also undertaken, in support of a wide range of archaeological

1Department of Archaeology, University of Sheffield, West Court, 2 Mappin Street, Sheffield S1 4DT, England, United Kingdom.
3Corresponding author. Email: jane.sidell@english-heritage.org.uk.
4Centre for Isotope Research, Rijksuniversiteit Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands.
5Chronologies, 25 Onslow Road, Sheffield, S11 7AF, England, United Kingdom.
6Scottish Universities Environmental Research Centre (SUERC), Scottish Enterprise Technology Park, East Kilbride G75 0QF, Scotland, United Kingdom.
7Research Laboratory for Archaeology, University of Oxford, Dyson Perrins Building, South Parks Road, Oxford OX1 3QY, England, United Kingdom.

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projects (see e.g. Bayliss et al. 2007a, 2008). This includes field-testing of methodological developments prior to their transfer to the wider Historic Environment sector in England, in addition to more usual site-driven research and quality assurance programs. The $^{14}$C results from individual sites are routinely incorporated into Bayesian chronological models (Bayliss and Bronk Ramsey 2004) where prior archaeological information about the relative ages of samples is available. The prior information may not only be from situations in which we have material with known-age increments (e.g. tree rings) but from archaeological sites where we might know that samples lie in a particular order or relate to a single phase of activity (Bronk Ramsey 2008).

Following a number of previously successful wiggle-matching studies using accelerator mass spectrometry (AMS) dating for oak timbers (Arnold et al. 2006; Bayliss et al. 2006, forthcoming; Hamilton et al. 2007), the samples from Jermyn Street were considered to have additional research potential. This material not only provided known-age material, but also fell on a part of the calibration curve where single-year data were available (Stuiver 1993) and consisted of resinous conifers, which might require extensive pre-treatment for such accurate dating (Hoper et al. 1998). Consequently, this material was selected for $^{14}$C measurements, assessing agreement between laboratories, and wiggle-matching.

Sample 116.27, a slice from a timber with bark edge and 303 growth rings, was selected for the study following the subsequent reanalysis of its previously unmeasured outermost rings (Tyers, unpublished data). The timber matched well with reference chronologies from southern and eastern Sweden, and it was decided that single-year tree-ring samples (roughly decadally separated) would
be submitted for $^{14}$C dating and wiggle-matching. While sampling very narrow individual growth rings was challenging, 18 samples were obtained and sent at random to the Oxford Radiocarbon Accelerator Unit (OxA-), the Scottish Universities Environmental Research Centre, Glasgow (SUERC-), and the Centrum voor Isotopen Onderzoek, Groningen (GrA-). All the laboratories were informed that the samples came from a standing building and were known-age single-ring samples of Scots pine. They were not informed of the felling date of the timber (AD 1670) or the dates of the rings that were submitted to them for dating.

**RADIOCARBON SAMPLING AND ANALYSIS**

The samples dated by AMS at SUERC were prepared to $\alpha$-cellulose following the Belfast protocol (Hopper et al. 1998); combusted to carbon dioxide (Vandeputte et al. 1996), converted to graphite (Slota et al. 1987), and then measured as described by Xu et al. (2004). Samples dated by AMS at the Rijksuniversiteit Groningen were processed using the acid/alkali/acid protocol (Mook and Waterbolk 1985), combusted to carbon dioxide and graphitized as described by Aerts-Bijma et al. (1997, 2001), and then measured as described by van der Plicht et al. (2000). The samples dated by AMS at the Oxford Radiocarbon Accelerator Unit were prepared following the AAA protocol with additional bleaching to holocellulose (T Higham, personal communication) and dated as described by Bronk Ramsey et al. (2004).
All 3 laboratories maintain continual programs of quality assurance procedures, in addition to participation in international intercomparisons (Scott 2003). These tests indicate no laboratory offsets and demonstrate the validity of the precision quoted.

Stuiver and Quay (1981) indicated that without extensive pretreatment to remove resins and lignin, 14C measurements from conifer samples could be biased to slightly older ages. Hoper et al. (1998) further suggest that relatively depleted δ13C values (up to 1.9‰) may persist in the sample if it is insufficiently processed to remove lignins. It should be noted that Hoper et al. (1998) focused on New Zealand cedar (Librocedrus bidwilli), which may not have the same biological characteristics as other conifer species or those from other geographical zones.

The 14C results are presented in Table 1, and are quoted in accordance with the international standard known as the Trondheim Convention (Stuiver and Kra 1986). They are conventional 14C ages (Stuiver and Polach 1977).

### Calibration

The calibration of the results, relating the 14C measurements directly to calendar dates, is given in Table 1. All have been calculated using the calibration curve of Reimer et al. (2004) and the computer program OxCal v4.0.5 (Bronk Ramsey 1995, 1998, 2001, 2009). The calibrated date ranges for each sample given in Table 1 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 10 yr. The graphical distributions of the calibrated dates, given in outline in Figure 4 are derived from the probability method (Stuiver and Reimer 1993).

### Table 1 Results of 14C dating on single-ring samples of Pinus sylvestris from 107 Jermyn Street, London.

<table>
<thead>
<tr>
<th>Lab #</th>
<th>Ring #</th>
<th>14C age (BP)</th>
<th>δ13C (‰)</th>
<th>Calibrated date cal AD (95% confidence) IntCal04</th>
<th>Calibrated date cal AD (68% confidence) IntCal04</th>
<th>Posterior density estimate, cal AD (95% probability)</th>
<th>Actual date (AD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OxA-17254</td>
<td>128</td>
<td>337 ± 26</td>
<td>-25.4</td>
<td>1450–1650</td>
<td>1480–1540</td>
<td>1485–1510</td>
<td>1495</td>
</tr>
<tr>
<td>GrA-34748</td>
<td>168</td>
<td>315 ± 30</td>
<td>-26.2</td>
<td>1470–1650</td>
<td>1520–1540</td>
<td>1510–1555</td>
<td>1535</td>
</tr>
<tr>
<td>OxA-17253</td>
<td>188</td>
<td>271 ± 26</td>
<td>-23.7</td>
<td>1520–1800</td>
<td>1540–1560</td>
<td>1545–1570</td>
<td>1555</td>
</tr>
<tr>
<td>OxA-17252</td>
<td>203</td>
<td>344 ± 26</td>
<td>-24.0</td>
<td>1450–1650</td>
<td>1560–1580</td>
<td>1560–1585</td>
<td>1570</td>
</tr>
<tr>
<td>SUERC-14016</td>
<td>208</td>
<td>320 ± 25</td>
<td>-25.0</td>
<td>1470–1650</td>
<td>1560–1580</td>
<td>1560–1590</td>
<td>1575</td>
</tr>
<tr>
<td>GrA-34753</td>
<td>213</td>
<td>330 ± 30</td>
<td>-25.8</td>
<td>1450–1650</td>
<td>1570–1590</td>
<td>1555–1600</td>
<td>1580</td>
</tr>
<tr>
<td>GrA-34747</td>
<td>228</td>
<td>335 ± 30</td>
<td>-24.4</td>
<td>1450–1650</td>
<td>1580–1600</td>
<td>1570–1615</td>
<td>1595</td>
</tr>
<tr>
<td>OxA-17251</td>
<td>233</td>
<td>366 ± 26</td>
<td>-25.0</td>
<td>1440–1640</td>
<td>1590–1610</td>
<td>1590–1615</td>
<td>1600</td>
</tr>
<tr>
<td>GrA-35286</td>
<td>251</td>
<td>295 ± 30</td>
<td>-25.8</td>
<td>1490–1670</td>
<td>1600–1610</td>
<td>1580–1630</td>
<td>1608</td>
</tr>
<tr>
<td>SUERC-14026</td>
<td>253</td>
<td>380 ± 25</td>
<td>-24.7</td>
<td>1440–1630</td>
<td>1610–1630</td>
<td>1600–1635</td>
<td>1620</td>
</tr>
<tr>
<td>OxA-17250</td>
<td>263</td>
<td>352 ± 26</td>
<td>-23.9</td>
<td>1450–1640</td>
<td>1620–1640</td>
<td>1620–1645</td>
<td>1630</td>
</tr>
<tr>
<td>OxA-17249</td>
<td>293</td>
<td>175 ± 26</td>
<td>-23.6</td>
<td>1660–1960</td>
<td>1650–1670</td>
<td>1650–1675</td>
<td>1660</td>
</tr>
</tbody>
</table>
RESULTS

It is clear from Table 1 that for each sample the actual calendar date falls within the 2-σ range of the simple calibrated date. Figure 3 shows the difference between pairs of measurements on a single tree-ring from the same year produced during this study and by Stuiver (1993). The paired measurements are in excellent agreement, and the results from all the single years are statistically consistent (following the method of Ward and Wilson 1978), except for those for AD 1550 (T' = 4.0; v = 1; T'(5%) = 3.8) and for AD 1660 (T' = 6.6; v = 1; T'(5%) = 3.8). Thus, there appears to be no significant offset between the measurements made for this study and equivalent data included in the calibration curve (Reimer et al. 2004). The single-year measurements of Stuiver (1993) were obtained by gas proportional counting of Douglas fir, from samples processed to α-cellulose (for the period in question here, see Stuiver 1993: Table 1). For this material, there also appears to be no significant difference between samples pretreated simply using acid/base/alkali, and those which underwent an additional bleaching stage.

Figure 3 Offsets between 14C results on single-years dated during this study and results on the same single-years dated by Stuiver (1993).

WIGGLE-MATCHING

A Bayesian approach, combining the 14C dates with the relative dating provided by the tree-ring analysis, was employed to wiggle-match the results (see Christen and Litton 1995; Bronk Ramsey et al. 2001; Galimberti et al. 2004). The technique used is a form of Markov chain Monte Carlo sampling, and has been applied using the program OxCal v 4.0.5. Details of the algorithms employed are available from the online manual (http://c14.arch.ox.ac.uk/) or in Bronk Ramsey (1995, 1998, 2001, 2009). The algorithm used in the models described below may be derived from the structures shown in Figures 4 to 8.
The chronological model for the dating of all samples is shown in Figure 4. It includes the relative dating information provided by tree-ring analysis, e.g. that OxA-17252 is 5 yr younger than SUERC-14016, and was calculated using IntCal04 (Reimer et al. 2004). The model has good overall agreement ($A_{comb} = 28.6\%$), and estimates that the timber was felled in cal AD 1660–1680 (95% probability; felling date; Figure 4), consistent with the felling date of AD 1670 produced by dendrochronology. The posterior density estimates for the formation of each dated tree-ring also match the actual dates for each ring suggested by dendrochronology (see Table 1), at both 68% and 95% probability. If the felling date for the timber, AD 1670, is also included in this model as “prior” information, then it still has good overall agreement ($A_{comb} = 23.6\%$; Figure 5).

In order to evaluate the internal consistency of measurements from each of the 3 laboratories, wiggle-matching the 3 sets of results obtained was undertaken separately. The resulting 3 chronological models are shown in Figure 6. They all show good agreement (SUERC $A_{comb} = 85.1\%$; Groningen $A_{comb} = 52.4\%$; Oxford $A_{comb} = 51.3\%$) and give accurate felling estimates for the timber (see...
Table 2). If the felling date is included in each chronological model they once again demonstrate good overall agreement (SUERC $A_{\text{comb}} = 67.4\%$; Groningen $A_{\text{comb}} = 38.0\%$; Oxford $A_{\text{comb}} = 35.9\%$). This confirms the accuracy of the quoted measurements suggested by comparison with the calibration data. The overall agreement $A_{\text{comb}}$ is a product of the individual agreement values for the samples in each wiggle-match. Each individual agreement value is a test for the goodness of fit (in effect a pseudo-Bayes factor) that relates the posterior density estimate distribution to the calibrated date distribution for individual measurements (Bronk Ramsey et al. 2001). The use of the a-priori felling date in the wiggle matches strongly effects the overall agreement ($A_{\text{comb}}$) of the models because it is informative prior information (Bayliss et al. 2007b).

**Wiggle-Matching and the Radiocarbon Calibration Curve**

IntCal04 (Reimer et al. 2004) uses a more sophisticated statistical method, based on a random walk model, for the estimation of errors on the calibration curve by interpolating data points at 5-yr bin widths using a smoothing function (Buck and Blackwell 2004). This introduces a small amount of smoothing to the data, although it better reflects the underlying data with an annual scale input when compared to IntCal98 (Bronk Ramsey et al. 2006). However, because the data points are interpolated using a smoothing function, they are not statistically independent.
In order to assess the effects of the statistical dependency between the data points in the IntCal04 calibration curve, the model (shown in Figure 4) was re-run using the IntCal98 calibration data set (Stuiver et al. 1998). The resulting model (see Figure 7) shows good agreement ($\Delta_{\text{comb}} = 25.1\%$ ($\Delta_{\text{m}} = 16.7.9\%$, $n = 18$) and produces an accurate estimate, cal AD 1650–1685 (95% probability; felling date; Table 3), for the felling of the timber. This demonstrates empirically that this theoretical statistical concern is perhaps unlikely to be of great practical significance when undertaking even highly constrained Bayesian models.

Table 2 Estimated felling dates obtained using data from each laboratory in isolation.

<table>
<thead>
<tr>
<th></th>
<th>IntCal04 (68% probability)</th>
<th>IntCal04 (95% probability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glasgow estimated felling date</td>
<td>cal AD 1655–1680</td>
<td>cal AD 1650–1685</td>
</tr>
<tr>
<td>Groningen estimated felling date</td>
<td>cal AD 1645–1675</td>
<td>cal AD 1645–1690</td>
</tr>
<tr>
<td>Oxford estimated felling date</td>
<td>cal AD 1665–1685</td>
<td>cal AD 1660–1685</td>
</tr>
<tr>
<td>All samples estimated felling date</td>
<td>cal AD 1660–1675</td>
<td>cal AD 1660–1680</td>
</tr>
</tbody>
</table>

In order to assess the effects of the statistical dependency between the data points in the IntCal04 calibration curve, the model (shown in Figure 4) was re-run using the IntCal98 calibration data set (Stuiver et al. 1998). The resulting model (see Figure 7) shows good agreement ($\Delta_{\text{comb}} = 25.1\%$ ($\Delta_{\text{m}} = 16.7.9\%$, $n = 18$) and produces an accurate estimate, cal AD 1650–1685 (95% probability; felling date; Table 3), for the felling of the timber. This demonstrates empirically that this theoretical statistical concern is perhaps unlikely to be of great practical significance when undertaking even highly constrained Bayesian models.
Finally, the analysis was repeated using the single-year data of Stuiver (1993; see Tables 2 and 3). Although as a single record, there is considerable random noise in this data set, the resultant model (shown in Figure 8) also exhibits good agreement ($A_{comb} = 54.7\%$; $A_n = 16.7\%$, $n = 18$; Figure 8) and provides an accurate estimate for the felling date of the timber of cal AD 1660–1675 (90% probability). As the data of Stuiver (1993) was from USA west coast wood and the wiggle-match material from higher-latitude Scandinavian material, we might expect to see slightly more recent 14C ages for the wiggle-match samples due to stratospheric-tropospheric exchange in high latitudes (Levin and Hesshaimer 2000; Kromer et al. 2001). The fact that the wiggle-match result is consistent with the dendrochronological date suggests that small regional offsets in 14C levels are not significant enough, in this period, to effect the calibration of 14C ages into calendar years.

Figure 7 Probability distributions of dates from timber slice 116.27 (IntCal98). The format is identical to that of Figure 4. The large square brackets down the left-hand side along with the OxCal keywords define the model exactly.

Table 3 Estimated felling dates using different calibration curves. *Posterior density estimates* from the model shown in Figure 5 were exactly the same using either IntCal04 or IntCal98.

<table>
<thead>
<tr>
<th>Curve</th>
<th>(68% probability)</th>
<th>(95% probability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IntCal04</td>
<td>cal AD 1660–1675</td>
<td>cal AD 1660–1680</td>
</tr>
<tr>
<td>IntCal98</td>
<td>cal AD 1655–1680</td>
<td>cal AD 1650–1685</td>
</tr>
<tr>
<td>Stuiver 1993</td>
<td>cal AD 1663–1666 (12%) or</td>
<td>cal AD 1656–1659 (4%) or</td>
</tr>
<tr>
<td></td>
<td>cal AD 1667–1673 (56%)</td>
<td>cal AD 1660–1675 (90%) or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cal AD 1676–1677 (1%)</td>
</tr>
</tbody>
</table>
The reproducibility of the analyses of these 14C data suggests that the existing calibration data and methodology are adequate for accurate wiggle-matching in the post-medieval period. This application may not, however, be typical as it falls during the currency of single-year calibration data, which only exist (at present) between AD 1510–1954.

**CONCLUSIONS**

This study has confirmed the agreement of the 14C measurements obtained from the 3 collaborating laboratories (Figure 9). It has established the potential that AMS wiggle-matching of single-year samples has for providing precise and accurate dating of post-medieval standing buildings that cannot be dated by dendrochronology. In addition, for relatively recent conifer timbers from buildings at least, these data suggest a full $\alpha$-cellulose extraction might not be essential for applications that require this level of accuracy. However, it is not yet clear whether this type of application can be carried out with the same expectation of absolute accuracy in earlier periods, beyond the limit of the single-year calibration data (currently AD 1510–1954).
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