**14C CALIBRATION IN THE 2ND AND 1ST MILLENNIA BC—EASTERN MEDITERRANEAN RADIOCARBON COMPARISON PROJECT (EMRCP)**

Bernd Kromer¹,² • Sturt W Manning³ • Michael Friedrich¹,⁴ • Sahra Talamo⁵ • Nicole Trano¹

**ABSTRACT.** We have measured additional known-age German oak samples in 4 intervals in the 2nd and 1st millennia BC to add to (and to replicate) parts of the international Northern Hemisphere radiocarbon calibration data set. In the 17th, 16th, and 12th centuries BC, our results agree well with IntCal04. In the 14th and 13th centuries BC, however, we observe a significant offset, with our results on average 27 yr older than IntCal04. The previously reported 14C offset between Anatolian juniper trees and central European oaks in the 9th and 8th centuries BC is smaller now, on the basis of our new measurements of German oak, but still evident. In the 17th and 16th centuries BC, the 14C ages from the Anatolian chronology agree well with IntCal04 and our new German oak data.

**INTRODUCTION**

An accurate chronology in the Late Bronze Age and early Iron Age is essential for a number of crucial sites and events in the archaeology of the eastern Mediterranean (Manning 1999; Manning et al. 2006), such as the controversy over the date of the Minoan eruption of Santorini, and claims of a discrepancy between physical dating methods and the historical Egyptian chronology (e.g. Bietak 2003; Wiener 2003; Bruins et al. 2009; Manning et al. 2009). Radiocarbon dating provides rather precise ages in this interval (e.g. Bronk Ramsey et al. 2004; Manning et al. 2006), yet it has been questioned by some whether the calibration of 14C ages to calendar ages could introduce uncertainties or biases, e.g. high-frequency fluctuations removed in the construction of the calibration data set IntCal04 (Reimer et al. 2004), or regional differences in the atmospheric 14C level between the eastern Mediterranean and central and northern Europe, since the 14C data in this period comprising the IntCal04 data set derive from either German oak or Irish oak. We therefore decided to remeasure some sections of known-age German oak samples, with increased resolution and the highest precision we could obtain in the Heidelberg radiocarbon laboratory. This exercise is part of the Eastern Mediterranean Radiocarbon Comparison Project (EMRCP) (Kromer et al. 2001; Manning et al. 2001, 2003, 2005); as part of this project we also compared and so anchored a 14C time series from the floating Bronze/Iron Age Anatolian conifer dendrochronology by 14C wiggle-matching with the 14C calibration curves IntCal98 (Kuniholm et al. 1996; Kromer et al. 2001; Manning et al. 2001, 2003) and IntCal04 (Manning et al. 2005, forthcoming; Manning and Kromer n.d., 2011). These data and the comparisons of the time series provide for an assessment of, and constraints for, any putative regional offsets in 14C ages between the Aegean and central Europe.

**TREE-RING SERIES AND METHODS**

We obtained 10- and 5-yr wood samples from the Hohenheim German oak chronology (Friedrich et al. 2004). The samples were milled and pretreated using a slightly modified de Vries method (NaOH overnight; HCl, NaOH, and HCl for 1 hr each; all at 80 °C) and, for all samples measured since 2005, bleached with NaClO₂ for cellulose. The wood was combusted in a Parr bomb, and the CO₂ was purified. The samples were measured for 9 to 12 days in our low-level gas counters (Kromer and Männich 1992). An overview of the calendar age ranges of the tree-ring sections is given in

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The interval 1650–1490 BC has been measured twice, first at decadal resolution in work between 1998 and 2001, and again between 2005 and 2008 in 5-yr increments. The decadal data of this interval are already part of IntCal04 (trees Sand, Ebensfeld, and Knetzgau in Tables 1 and 2).

Table 1 List of German oak trees employed for 14C measurements undertaken as part of the EMRCP.

<table>
<thead>
<tr>
<th>Interval BC</th>
<th>Tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1710–1661</td>
<td>Sand 21</td>
</tr>
<tr>
<td>1700–1651</td>
<td>Ebensfeld 99</td>
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<tr>
<td>1660–1491</td>
<td>Knetzgau 40</td>
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<tr>
<td>1649–1584</td>
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<td>1594–1555</td>
<td>Unterbrunn 24</td>
</tr>
<tr>
<td>1561–1492</td>
<td>Unterbrunn 25</td>
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<tr>
<td>1514–1480</td>
<td>Unterbrunn 3 D</td>
</tr>
<tr>
<td>1356–1300</td>
<td>Augsfeld 141</td>
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<td>1299–1250</td>
<td>Augsfeld 141A</td>
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<tr>
<td>1211–1306</td>
<td>Oberhaid 4</td>
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<tr>
<td>1159–1115</td>
<td>Bittenbrunn 2B</td>
</tr>
<tr>
<td>710–611</td>
<td>Baunach 62</td>
</tr>
<tr>
<td>756–617</td>
<td>Trieb 70</td>
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Figure 1 Raw data of IntCal04 (German oak measured in Seattle and Heidelberg, and Irish oak measured in Belfast) and the calibration data set IntCal04 (Reimer et al. 2004).

RESULTS AND DISCUSSION

The 14C results are listed in Table 2 and are shown in Figures 2 to 4. In several graphs, our data are compared with the calibration curve IntCal04 (solid line) and with subsets of the raw data of IntCal04, from which the averaged and smoothed data set IntCal04 was calculated (Buck and Blackwell 2004). In this age range, the data comprising IntCal04 come predominantly from (a) German oak measured before 1986 in the Seattle radiocarbon laboratory (Stuiver and Becker 1986, 1993;
Stuiver et al. 1998) and (b) Irish oak (Pearson and Stuiver 1986, 1993). In the interval 1650–1480 BC (Figure 1), we have in addition German oak measured in the Heidelberg laboratory between 1998 and 2001 (Reimer et al. 2004). Hence, our new 14C measurements on German oak allow a check on the long-term stability of the Heidelberg laboratory, and for a consideration of comparisons on same wood samples between the Seattle and Heidelberg laboratories, and between measurements on different tree-ring chronologies in the case of the Irish oak. The data sets are evaluated using paired t tests. We note that the data of IntCal04 have been obtained by combining the measurements, weighted in a random walk model and resampled to obtain the 5-yr resolution of IntCal04 (Buck and Blackwell 2004); hence, the degrees of freedom in the t test need to be adjusted (lowered) to account for the autocorrelation in IntCal04: see Table 3.

Table 2 14C data from German oak samples measured as part of the EMRCP.

<table>
<thead>
<tr>
<th>Tree</th>
<th>Start/end BC</th>
<th>14C age</th>
<th>Error</th>
<th>δ13C</th>
<th>Hd-</th>
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Table 3 14C data from German oak samples measured as part of the EMRCP.

<table>
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<tr>
<th>Site</th>
<th>Tree</th>
<th>Start BC</th>
<th>End BC</th>
<th>14C age</th>
<th>Error</th>
<th>δ13C</th>
<th>Hd-</th>
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<th>Error</th>
<th>δ13C</th>
<th>Tree</th>
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Table 2 14C data from German oak samples measured as part of the EMRCP. (Continued)

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</table>

(Continued)
Interval 1650–1480 BC

Our new data (Figure 2) are slightly lower (13 yr) than IntCal04, with the nominal differences smaller when compared with the German oak measured in Seattle than with the Irish oak measured at Belfast; however, the differences between the data sets are statistically not significant. The observed standard deviation is compatible within the reported errors.

Interval 1360–1210 BC

Our new data (Figure 3a) are higher than IntCal04 by 27 yr, and the difference is significant. We confirmed our results in the interval around 1280 BC where the 2 trees employed for wood samples

<table>
<thead>
<tr>
<th>Site</th>
<th>Tree</th>
<th>Start BC</th>
<th>End BC</th>
<th>14C age</th>
<th>Error</th>
<th>(\delta^{13}C)</th>
<th>Hd-</th>
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<td>Augsfeld</td>
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Table 3 Differences in \(^{14}C\) age of pairs of same calendar age tree-ring samples between Heidelberg (Hd) and IntCal04 (5-yr resolution), Heidelberg and Seattle (QL, 10-yr resolution), Heidelberg and Belfast (UB, 20-yr resolution), and Heidelberg measurements obtained between 2007–2009 compared to those made in 1998–2001 (Hd2008-Hd2000). The format is mean difference/observed standard deviation/expected standard deviation/number of pairs.

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<td>(1.6/39/31.8/19a)</td>
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<td>1160–1110 BC</td>
<td>5.4/16.6/20.2/10</td>
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*aIncluding decades 1710–1701 BC and 1670–1660 BC with Hd-QL >70 yr.

Interval 1650–1480 BC

Our new data (Figure 2) are slightly lower (13 yr) than IntCal04, with the nominal differences smaller when compared with the German oak measured in Seattle than with the Irish oak measured at Belfast; however, the differences between the data sets are statistically not significant. The observed standard deviation is compatible within the reported errors.

Interval 1360–1210 BC

Our new data (Figure 3a) are higher than IntCal04 by 27 yr, and the difference is significant. We confirmed our results in the interval around 1280 BC where the 2 trees employed for wood samples
overlap. The difference is strongest in the younger half of the interval, where also the variance of the raw data entering IntCal04 is high (Figure 3b), and around the $^{14}$C age inversion at 1325 BC where our 5-yr data indicate a higher amplitude than expressed in IntCal04. We note that the $^{14}$C ages from the Anatolian juniper chronology, when wiggle-matched against IntCal04, also show a similar offset across these 150 yr (Figure 3c).
Figure 3b Same as Figure 3, but including the raw data (filled circles) of IntCal04

Figure 3c Same as Figure 3a, but including the ¹⁴C ages from the wiggle-matched Anatolian juniper dendrochronology built over this time interval from samples from Gordion (see text below). The plot updates the situation for the Anatolian data set compared with previous work (Manning et al. 2003).
Interval 1160–1110 BC

In this interval our new data agree fully with IntCal04 (Figure 4). We confirm the existence of the $^{14}$C age inversion at 1135 BC, which we encountered in several exercises to match floating tree-ring sequences to the calibration curve.

14C Series from the East Mediterranean Bronze-Iron Tree-Ring Chronology

We reported previously on the anchoring of a long juniper tree-ring chronology from several sites in Anatolia by $^{14}$C wiggle-matching (Kuniholm et al. 1996; Manning et al. 2001, 2003, 2005; also Newton and Kuniholm 2004), which provided calendar ages for the chronology within a very narrow confidence interval of 1 decade at 3 $\sigma$ (99.7%) (ring 777 of the dendrochronology dated to between 1734 and 1724 BC against IntCal98). A very slightly revised assessment using a subsequent larger data set and IntCal04 now places ring 776 at $\sim$1729 $\pm$6/8 BC within approximate 95.4% confidence limits (Manning et al., forthcoming)—a best-fit point just 1 or 2 yr older than the fit found previously in Manning et al. (2001, 2003). A number of additional analyses of samples from this dendrochronology have been made and are shown here in Figures 3c, 5, and 6. As these data are not known-age (rather $^{14}$C wiggle-matched within a small dating envelope), they are not reported here in detail in a paper that primarily provides an additional calibration data set (Table 2). Instead, the $^{14}$C data from the Gordion area dendrochronology are reported in Manning et al. (forthcoming), the data covering approximately 1730–1480 BC are discussed in Manning and Kromer (n.d.), and a general discussion of all $^{14}$C analyses at Gordion will appear in Manning and Kromer (2011). Nonetheless, it is useful here in the context of our new measurements to discuss briefly the question of a regional offset for $^{14}$C in the eastern Mediterranean since this is a topic of some significance and interest.
In Figure 5, we show previously published (Manning et al. 2003) and recently measured data of the Anatolian chronology with the absolute date based on the $^{14}$C wiggle-match (these data are presented in Manning et al., forthcoming). It is obvious from the comparison that within the error margin of IntCal04 (13 yr) and our data (15…18 yr), there is no evidence for any substantive difference in $^{14}$C levels between central and northern Europe (Germany, Ireland: the source of the trees in this section of IntCal04) and Anatolia in the 17th and 16th centuries BC.

For the 8th and 9th centuries BC, we previously found an indication of a small offset between the Anatolian chronology and the standard Northern Hemisphere calibration curve IntCal98 (Kromer et al. 2001; Manning et al. 2001, 2003). We subsequently remeasured German oak samples for this age range in addition, and found slightly older ages, especially for a segment that was covered only by bidecadal measurements in IntCal98 (Manning et al. 2005). The new data are already part of IntCal04, and we can now repeat the comparison with the updated information, shown in Figure 6.

The Anatolian juniper still show elevated $^{14}$C ages, albeit with smaller differences to IntCal04 (versus against IntCal98), because of the revised German oak data between 750 and 800 BC. We interpret the difference to be caused by phase shifts in the uptake of carbon into the cellulose of tree rings amplified by the climate impact at this interval of the major solar minimum centered around 765 BC, with the relevant Anatolian trees (junipers from likely lower- to mid-elevation loci within reasonable distances of the archaeological contexts at Gordion from which the timbers were recovered)
forming the major part of their growth ring in spring and earlier summer, whereas the German oaks show a more equal distribution over the growing season and start their growth a little later (German oak growth period overall mainly May through August). There is evidence for a (natural) seasonal variation of atmospheric $^{14}$C level of a few ‰ (Levin et al. 2009). Normally, this variation in plant samples is below the detection limit even with highest $^{14}$C precision, but during times of exceptionally low solar activity, such as in the 1st millennium BC, the flux of stratospheric $^{14}$C into the troposphere is enhanced, and we may detect this signal in the special growing season configuration of lower- to mid-elevation Anatolian juniper versus German oak.

CONCLUSIONS

We have remeasured crucial intervals of the $^{14}$C calibration curve in the 1st and 2nd millennia BC with increased resolution and high precision. For the 17th and 16th centuries BC, we confirm the $^{14}$C age pattern as constructed in IntCal04 from 3 data sets. In this interval, we do not see evidence for smoothing of real high-frequency $^{14}$C age fluctuations. In the 14th and 13th centuries BC, however, we observe a significant offset, with our results on average 27 yr older than IntCal04. We also observe some evidence for real $^{14}$C fluctuations over this interval (e.g. around 1325 BC) and in the 12th century BC (around 1135 BC), which appear overly smoothed away in the current IntCal04.
curve. The previously reported offset between Anatolian juniper trees and central European oaks in the 9th and 8th centuries BC is now smaller, on the basis of our new measurements of German oak, but still exists. In the 17th and 16th centuries BC, the $^{14}$C ages from the Anatolian juniper chronology agree well with IntCal04 and our new German oak data, as does a 7-decade time series of west Anatolian (near coastal) oak reported from Miletos (Bronk Ramsey et al. 2004; Manning et al. 2006; see further in Manning et al., forthcoming; Manning and Kromer n.d.); these findings leave no room for a purported (Keenan 2002) regional depletion of $^{14}$C ages in the eastern Mediterranean during this time.

ACKNOWLEDGMENTS

We thank INSTAP for the primary funding of the Eastern Mediterranean Radiocarbon Comparison Project (EMRCP), and NSERC for 2 years of support. The German oak samples measured in 1998 to 2001 were prepared by Marco Spurk. We thank Peter Ian Kuniholm, Maryanne Newton, Jennifer Watkins, and Charlotte Pearson, and the many others at the Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology over many years, who have worked on the Gordion area chronology and samples.

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