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

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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 ^{14}C 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 ^{14}C 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 ^{14}C 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 ^{14}C level between the eastern Mediterranean and central and northern Europe, since the ^{14}C 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 ^{14}C time series from the floating Bronze/Iron Age Anatolian conifer dendrochronology by ^{14}C wiggle-matching with the ^{14}C 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 ^{14}C 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 $NaClO_2$ for cellulose. The wood was combusted in a Parr bomb, and the CO_2 was purified. The samples were measured for 9 to 12 days in our low-level gas counters (Kromer and Münnich 1992). An overview of the calendar age ranges of the tree-ring sections is given in

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Table 1. 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 ^{14}C measurements undertaken as part of the EMRCP.

Interval BC	Tree
1710–1661	Sand 21
1700–1651	Ebensfeld 99
1660–1491	Knetzgau 40
1649–1584	Unterbrunn 12A
1594–1555	Unterbrunn 24
1561–1492	Unterbrunn 25
1514–1480	Unterbrunn 3 D
1356–1300	Augsfeld 141
1299–1250	Augsfeld 141A
1211–1306	Oberhaid 4
1159–1115	Bittenbrunn 2B
710–611	Baunach 62
756–617	Trieb 70

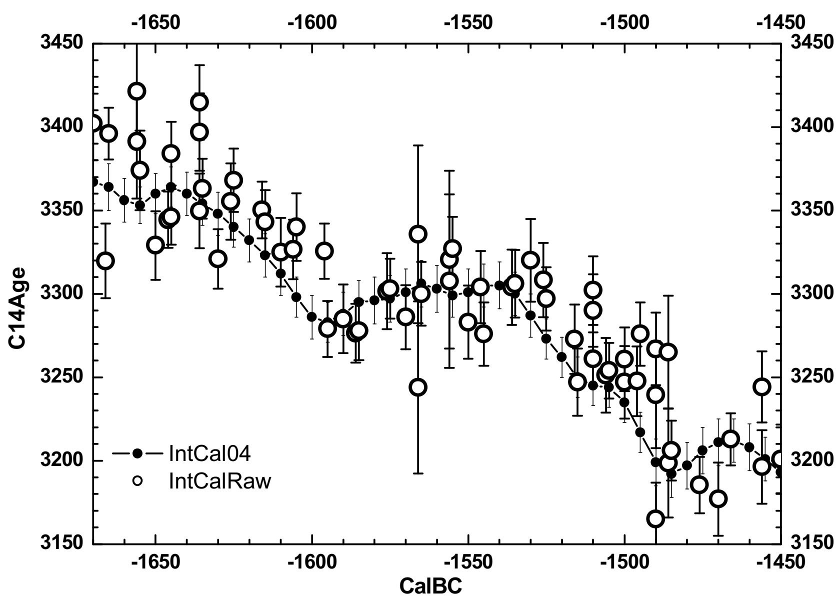

Figure 1 Raw data of IntCal04 (German oak measured in Seattle and Heidelberg, and Irish oak measured in Belfast) and the calibration data set IntCal04 (Reimer et al. 2004).

RESULTS AND DISCUSSION

The ^{14}C 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 ^{14}C 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 ^{14}C data from German oak samples measured as part of the EMRCP.

Tree	Start/end BC	^{14}C age	Error	$\delta^{13}C$	Hd-		
Ebensfeld	1710–1701	3471	15	–25.97	19803		
Ebensfeld	1700–1691	3408	15	–25.68	20053		
Ebensfeld	1690–1681	3396	15	–25.51	19800		
Ebensfeld	1680–1671	3403	16	–25.84	20054		
Ebensfeld	1670–1661	3386	15	–25.39	19804		
Ebensfeld	1670–1661	3409	21	–26.24	20098		
Ebensfeld	1660–1651	3385	16	–25.38	19811		
Ebensfeld	1650–1641	3364	15	–25.42	20052		
Ebensfeld	1640–1631	3368	16	–26.11	19858		
Ebensfeld	1630–1621	3343	16	–25.9	20123		
Ebensfeld	1620–1611	3340	17	–25.59	20010		
Ebensfeld	1610–1601	3279	14	–24.96	19997		
Ebensfeld	1600–1591	3280	14	–25.27	20012		
Ebensfeld	1590–1581	3303	15	–26.18	20089		
Ebensfeld	1580–1571	3300	16	–25.54	20000		
Ebensfeld	1570–1561	3326	16	–26.39	20094		
Ebensfeld	1560–1551	3276	16	–26.73	20097		
Ebensfeld	1550–1541	3307	17	–25.53	20009		
Ebensfeld	1540–1531	3297	16	–26.44	20102		
Ebensfeld	1530–1521	3248	17	–25.46	19996		
Ebensfeld	1520–1511	3254	14	–25.54	20122		
Ebensfeld	1510–1501	3276	16	–25.41	20129		
Ebensfeld	1500–1491	3206	15	–25.08	19994		
Site	Tree	Start BC	End BC	^{14}C age	Error	$\delta^{13}C$	Hd-
Bittenbrunn	2B	1160	1156	2950	13	–23.87	27203
Bittenbrunn	2B	1155	1151	2929	13	–23.74	27196
Bittenbrunn	2B	1150	1146	2943	13	–23.62	27202
Bittenbrunn	2B	1145	1141	2950	13	–23.65	27201
Bittenbrunn	2B	1140	1136	2973	14	–23.92	27206
Bittenbrunn	2B	1135	1131	2940	18	–23.88	27207
Bittenbrunn	2B	1130	1126	2963	15	–24.63	27208
Bittenbrunn	2B	1125	1121	2923	15	–24.2	27245
Bittenbrunn	2B	1120	1116	2944	15	–24.86	27254
Bittenbrunn	2B	1115	1111	2916	14	–24.02	27253
Site	Start BC	End BC	^{14}C age	Error	$\delta^{13}C$	Tree	Hd-
Unterbrunn	–1649	–1645	3358	23	–25.09	12A	26629
Unterbrunn	–1644	–1640	3369	19	–25.36	12A	26628
Unterbrunn	–1639	–1635	3326	18	–25.34	12A	26647

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Table 2 ^{14}C data from German oak samples measured as part of the EMRCP. *(Continued)*

Site	Start BC	End BC	^{14}C age	Error	δ^{13}C	Tree	Hd-
Unterbrunn	–1634	–1630	3344	17	–25.82	12A	26646
Unterbrunn	–1629	–1625	3354	15	–24.57	12A	26660
Unterbrunn	–1624	–1620	3313	15	–24.75	12A	26661
Unterbrunn	–1619	–1615	3325	14	–24.75	12A	26665
Unterbrunn	–1614	–1610	3296	12	–24.96	12A	26666
Unterbrunn	–1609	–1605	3282	12	–24.7	12A	26696
Unterbrunn	–1604	–1600	3297	14	–24.78	12A	26697
Unterbrunn	–1599	–1595	3290	13	–24.71	12A	26723
Unterbrunn	–1594	–1590	3271	14	–24.72	24 B2	27057
Unterbrunn	–1594	–1590	3258	23	–24.43	12A	26725
Unterbrunn	–1589	–1585	3261	14	–24.25	24 B2	27056
Unterbrunn	–1589	–1585	3273	19	–24.75	12A	26727
Unterbrunn	–1584	–1580	3293	12	–24.43	24 B2	27052
Unterbrunn	–1584	ca –1577	3278	21	–26.21	12A	26728
Unterbrunn	–1579	–1575	3312	16	–24.52	24 B2	27038
Unterbrunn	–1574	–1570	3302	13	–24.46	24 B2	27053
Unterbrunn	–1569	–1565	3288	15	–24.56	24 B2	26852
Unterbrunn	–1564	–1560	3286	15	–25.24	24 B2	26853
Unterbrunn	–1559	–1555	3283	13	–22.77	25 B	26839
Unterbrunn	–1554	–1550	3311	12	–23.78	25 B	26840
Unterbrunn	–1549	–1545	3263	16	–24.03	25 B	26809
Unterbrunn	–1544	–1540	3259	15	–23.86	25 B	26812
Unterbrunn	–1539	–1535	3300	15	–23.86	25 B	26813
Unterbrunn	–1534	–1530	3294	20	–24.15	25 B	26772
Unterbrunn	–1529	–1525	3246	12	–25	25 B	26771
Unterbrunn	–1524	–1520	3266	14	–24.55	25 B	26770
Unterbrunn	–1519	–1515	3262	22	–24.35	25 B	26763
Unterbrunn	–1514	–1510	3284	14	–24.75	25 B	26764
Unterbrunn	–1509	–1505	3228	16	–25.22	25 B	26765
Unterbrunn	–1504	–1500	3208	21	–24.89	25 B	26739
Unterbrunn	–1504	–1500	3236	17	–24.52	3 D	27073
Unterbrunn	–1499	–1495	3199	13	–24.31	3 D	27076
Unterbrunn	–1494	–1490	3193	13	–22.96	3 D	27065
Unterbrunn	–1489	–1485	3183	15	–23.23	3D	27066
Unterbrunn	–1484	–1480	3197	15	–23.46	3 D	27075

Site	Tree	Start BC	End BC	^{14}C age	Error	δ^{13}C	Hd-
Augsfeld	141	–1279	–1275	3045	20	–23.55	26749
Augsfeld	141	–1284	–1280	3046	16	–24.45	25175
Augsfeld	141	–1299	–1295	3064	22	–25.04	25192
Augsfeld	141	–1294	–1290	3065	18	–24.94	25191
Augsfeld	141	–1289	–1285	3053	14	–24.46	25174
Augsfeld	141A	–1356	–1350	3071	15	–27.09	24874
Augsfeld	141A	–1309	–1305	3119	16	–25.54	24869
Augsfeld	141A	–1304	–1300	3112	20	–25.99	24879
Augsfeld	141A	–1349	–1345	3072	17	–26.89	24880
Augsfeld	141A	–1339	–1335	3099	14	–26.08	24887
Augsfeld	141A	–1334	–1330	3113	13	–26.21	24838
Augsfeld	141A	–1329	–1325	3098	17	–26.04	24840
Augsfeld	141A	–1324	–1320	3091	13	–25.76	24841

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Table 2 ^{14}C data from German oak samples measured as part of the EMRCP. *(Continued)*

Site	Tree	Start BC	End BC	^{14}C age	Error	δ^{13}C	Hd-
Augsfeld	141A	–1319	–1315	3085	11	–25.29	24858
Augsfeld	141A	–1314	–1310	3088	12	–25.06	24920
Augsfeld	141A	–1344	–1340	3070	14	–26.14	24878
Site	Tree	Start BC	End BC	^{14}C age	Error	δ^{13}C	Hd-
Oberhaid	4	–1310	–1306	3097	21	–25.71	25945
Oberhaid	4	–1270	–1266	3042	13	–25.32	25902
Oberhaid	4	–1275	–1271	3019	13	–24.25	25912
Oberhaid	4	–1280	–1276	3031	15	–24.37	25918
Oberhaid	4	–1285	–1281	3050	13	–24.1	25917
Oberhaid	4	–1290	–1286	3081	17	–23.99	25934
Oberhaid	4	–1295	–1291	3042	18	–23.94	25935
Oberhaid	4	–1265	–1261	3028	12	–24.31	25901
Oberhaid	4	–1305	–1301	3022	17	–24.08	25944
Oberhaid	4	–1245	–1241	3013	15	–26.11	25894
Oberhaid	4	–1225	–1221	3011	12	–26.2	25875
Oberhaid	4	–1220	–1216	2957	14	–26.07	25876
Oberhaid	4	–1215	–1211	3018	23	–25.62	25877
Oberhaid	4	–1250	–1246	3037	13	–25.49	25896
Oberhaid	4	–1240	–1236	3049	13	–25.34	25893
Oberhaid	4	–1230	–1226	2986	15	–26.12	25888
Oberhaid	4	–1235	–1231	3016	14	–25.9	25891
Oberhaid	4	–1300	–1296	3054	20	–23.82	25938
Oberhaid	4	–1255	–1251	3001	12	–24.802	25897
Oberhaid	4	–1260	–1256	3018	11	–24.62	25900

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.

Interval	Hd-IntCal04	Hd-QL	Hd-UB	Hd2008-Hd2000
1650–1480 BC	–13.9/17.7/20.3/34	–8.2/29.2/31.8/21 (1.6/39/31.8/19[a])	–19.0/30.4/26.3/11	–13/22.7/25.1/16
1360–1210 BC	26.9/22.9/21.8/29	22.6/28.6/27.1/13	25.6/39.5/27.5/6	
1160–1110 BC	5.4/16.6/20.2/10			

[a]Including 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

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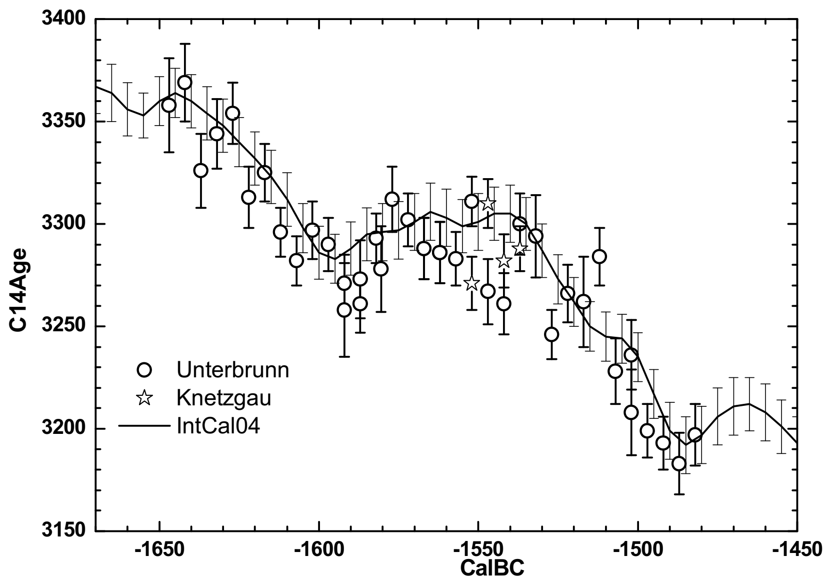

Figure 2 German oak ^{14}C ages measured in Heidelberg (trees Unterbrunn and Knetzgau, open circles and stars, respectively) compared with IntCal04 (solid line and thin error bars).

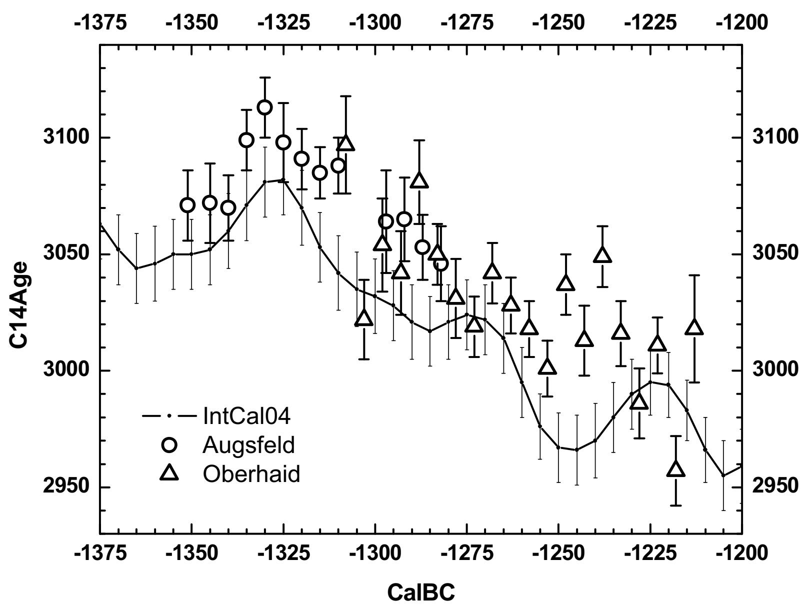

Figure 3a German oak ^{14}C ages measured in Heidelberg (trees Augsfeld and Oberhaid, open circles and triangles, respectively) compared to IntCal04 (solid line and thin error bars).

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).

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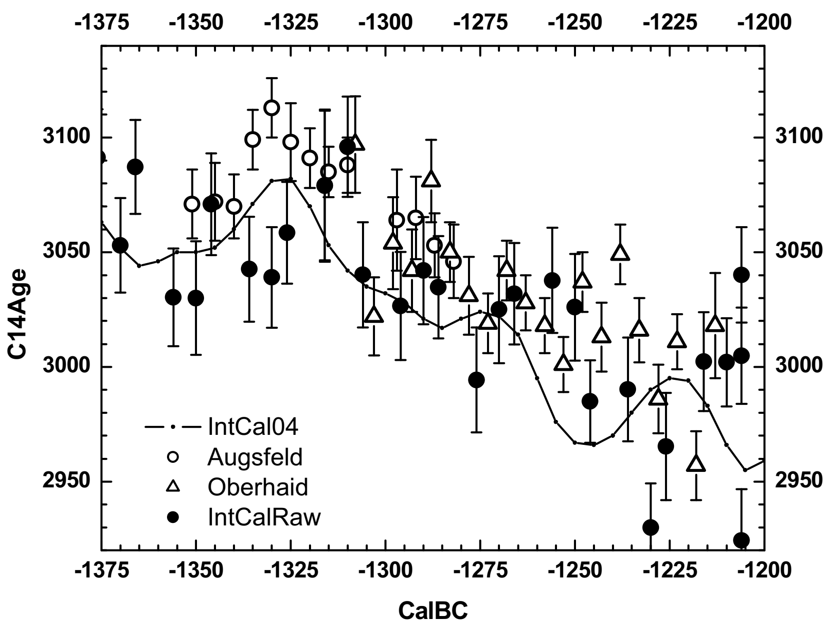

Figure 3b Same as Figure 3, but including the raw data (filled circles) of IntCal04

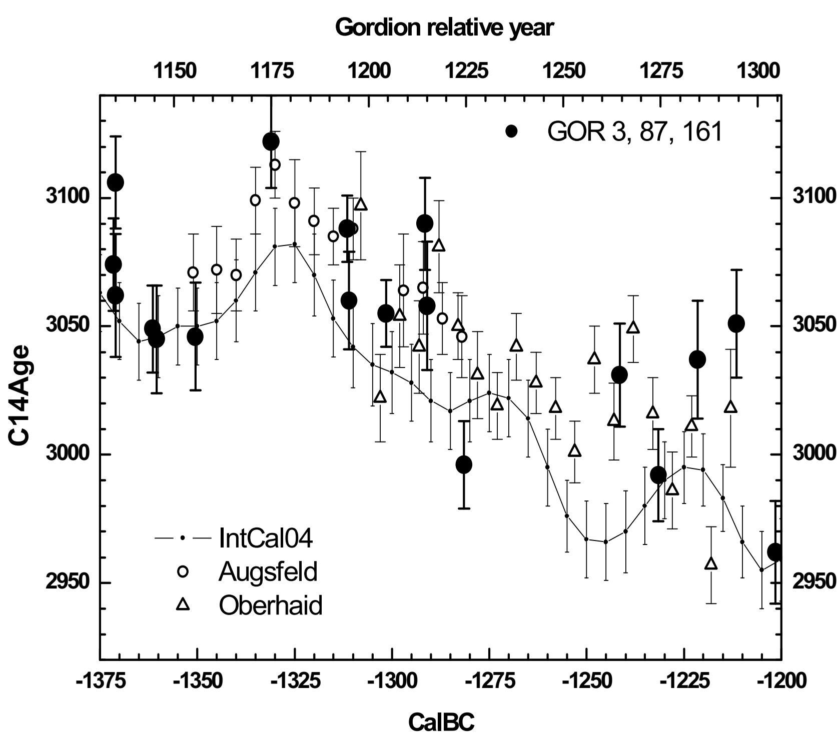

Figure 3c Same as Figure 3a, but including the ^{14}C ages from the wiggle-matched Anatolian juniper dendrochronology built over this time interval from samples from Gordion (see text below). The plot updates the situation for the Anatolian data set compared with previous work (Manning et al. 2003).

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.

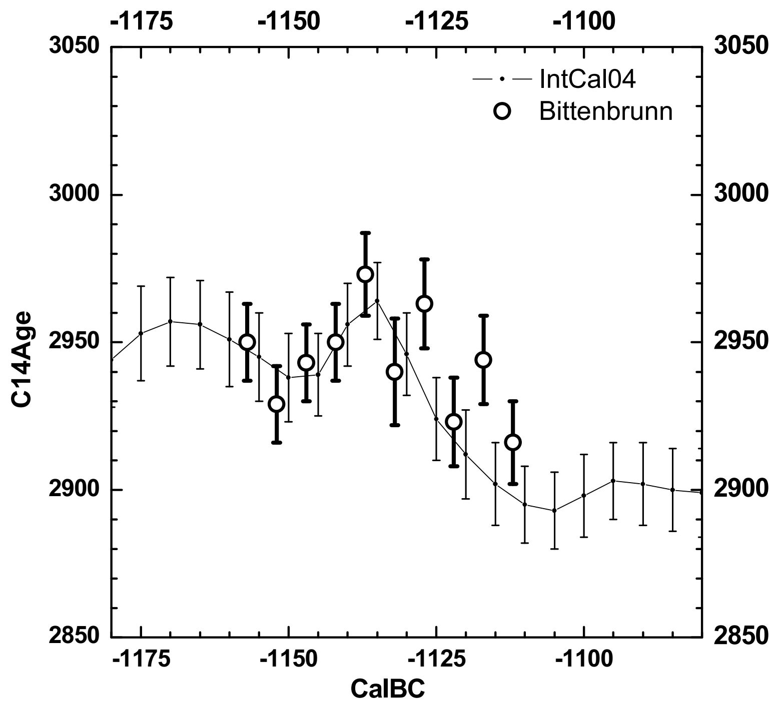

Figure 4 Detail extracted from Figure 3a showing the German oak ^{14}C ages measured in Heidelberg (open circles) compared with IntCal04 (solid line and thin error bars).

^{14}C 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 σ (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 ~1729 +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.

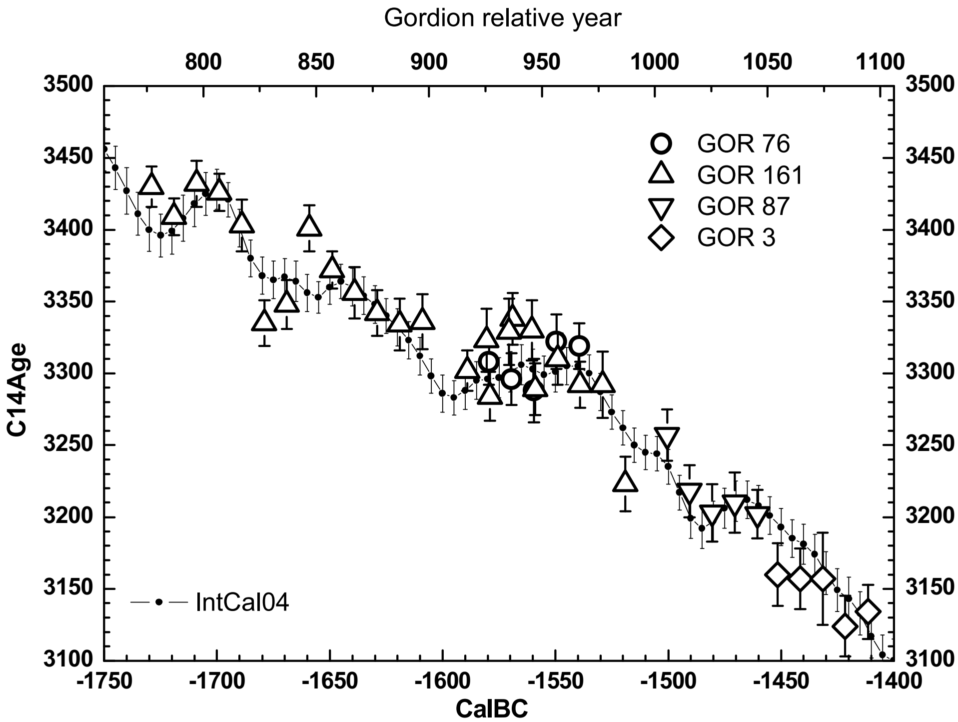

Figure 5 Comparison of ^{14}C ages from juniper tree rings (trees from the dendrochronology identified) from the Gordion area dendrochronology as wiggle-matched against IntCal04 (for data, see Manning et al., forthcoming; Manning and Kromer n.d.). For the Gordion dendrochronology, see Bannister (1970); Kuniholm (1977); Kuniholm and Newton (2011). For previous ^{14}C-dendro work and data on samples from the Gordion dendrochronology, see Kuniholm et al. (1996); Kromer et al. (2001); Manning et al. (2001, 2003, 2005).

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)

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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.

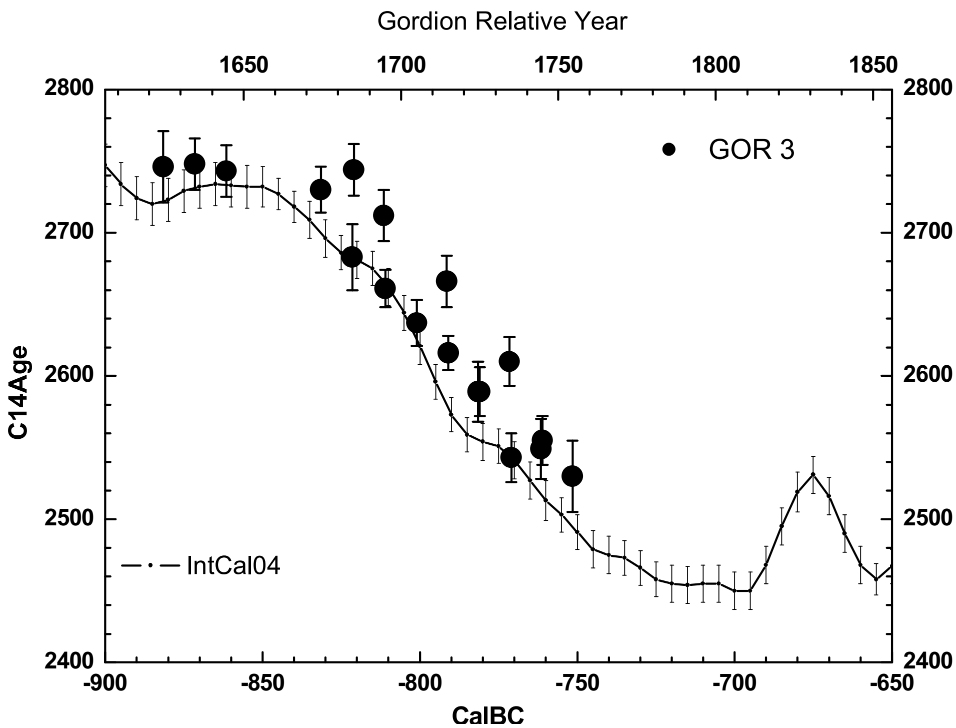

Figure 6 Comparison of the ^{14}C ages from samples from the Gordion dendrochronology versus IntCal04. The Gordion data are placed in calendar terms on the basis of a ^{14}C-wiggle-match of the overall ^{14}C-dendro data set from Gordion and especially on the basis of the data centered Gordion relative years 776.5 to 1145.5 (see Figure 5; for details see Manning et al., forthcoming)—with the calendar placement within 0–2 yr versus the best fits reported previously (Manning et al. 2001, 2003). The offset reported previously in the 9th and 8th centuries BC (Kromer et al. 2001; Manning et al. 2001) continues to be evident, but repeated measurements now indicate a smaller average offset than first reported (this is partly as the IntCal04 curve reflects changes made in this time interval to the German oak record because of the work by this project: Manning et al. 2005).

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.

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