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^{14}C RECORD AND WIGGLE-MATCH PLACEMENT FOR THE ANATOLIAN (GORDION AREA) JUNIPER TREE-RING CHRONOLOGY ~1729 TO 751 CAL BC, AND TYPICAL AEGEAN/ANATOLIAN (GROWING SEASON RELATED) REGIONAL ^{14}C OFFSET ASSESSMENT

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ABSTRACT. The East Mediterranean Radiocarbon (inter-)Comparison Project (EMRCP) has measured the ^{14}C ages of a number of sets of tree rings from the Gordion Area dendrochronology from central Anatolia at the Heidelberg Radiocarbon Laboratory. In several cases, multiple measurements were made over a period from the 1980s to 2009. This paper presents the final data set from this work (128 high-precision measurements), and considers (i) the relationship of these data against the standard Northern Hemisphere ^{14}C calibration data set (IntCal09), and (ii) the optimum calendar dating of this floating tree-ring record on the basis of the final set of high-precision ^{14}C data. It finds good agreement between the Anatolian data and IntCal09 in some important intervals (e.g. ~1729 to 1350 cal BC) and observes one period (9th–8th centuries BC) where there appears to be some indication of a regional/growing season signal, and another period (later 14th–13th centuries BC) where IntCal09 may not best reflect the real ^{14}C record. The scale of the typical growing-season-related regional ^{14}C offset (ΔR) between the Aegean/Anatolian region and IntCal09 is also assessed (for the mid-2nd millennium BC and mid-2nd millennium AD), and found to be usually minor (at times where there are no major additional forcing factors and/or issues with the IntCal09 data set): of the order of 2–4 ± 2–4 yr.

INTRODUCTION

A long juniper dendrochronology for the 2nd and earlier 1st millennia BC has been constructed from timbers recovered by archaeological exploration at and around the site of Gordion (modern Yassıhöyük) (Figure 1), central Turkey (Bannister 1970; Kuniholm 1977; Kuniholm and Newton n.d.). At present, this dendrochronology is floating because it does not link with absolutely dated tree-ring series. Over the last 3 decades, a program of ^{14}C dating has sought (among other things) to enable the near-absolute best dating of this dendrochronology in calendar years by "wiggle-matching" against the IntCal calibration curves (first in a published paper against the 1993 decadal record, then IntCal98, and subsequently IntCal04: Kuniholm et al. 1996; Kromer et al. 2001, 2010; Manning et al. 2001, 2003, 2005). The near-absolute placement of this dendrochronology in turn dates a number of important archaeological sites/monuments (Manning et al. 2001; Newton and Kuniholm 2004), and also allows assessment of regional Anatolian-east Mediterranean atmospheric ^{14}C levels across this time period. This paper presents a final publication of record for the work of the East Mediterranean Radiocarbon (inter-)Comparison Project (EMRCP) on the Gordion Area dendrochronology.

TREE-RING DATA AND METHODS

The Gordion Area juniper dendrochronology was developed first by Bannister (1970) and independently and subsequently by Kuniholm (1977), with the most recent detailed statement in Kuniholm and Newton (n.d.). For the EMRCP, wood from 7 different trees has been employed (Table 1). These samples all crossdate securely against the overall Gordion Area dendrochronology. We merely sum-

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Figure 1 Map of the eastern Mediterranean region indicating the location of the site of Gordion

Table 1 The 7 dendrochronological samples (trees and the radii therefrom) employed in this study from the Gordion Area dendrochronology (Bannister 1970; Kuniholm 1977; Kuniholm and Newton n.d.). For a summary of the crossdating, see Table 2. The center of the Midas Mound Tumulus is approximately located at 39°39′14″N and 31°59′53″E using WGS84. On the Midas Mound Tumulus, its excavation, and conservation, see Young (1981) and Liebhart and Johnson (2005).

Tree	Species	Context	Relative rings
GOR-2	*Juniperus foetidissima*	Midas Mound Tumulus, W. outer wall, log nr 4 from bottom	1279–1709
GOR-3	*Juniperus excelsa*	Midas Mound Tumulus, W. outer wall, log nr 3 from bottom	999–1763
GOR-36	*Juniperus excelsa*	Midas Mound Tumulus, W. outer wall, log nr 5 from bottom	993–1645
GOR-76	*Juniperus excelsa*	Midas Mound Tumulus, E. outer wall, log nr 7 from bottom	847–1676
GOR-83	*Juniperus excelsa*	Midas Mound Tumulus, S. outer wall, log nr 6 from bottom	1346–1762
GOR-87	*Juniperus excelsa*	Midas Mound Tumulus, S. outer wall, log nr 7 from bottom	904–1568
GOR-161	*Juniperus excelsa*	Kızlarkaya Tumulus A, plank from wooden walls of a tomb that had been robbed and was then excavated	737–1599

marize here the crossdating of the 7 long-lived samples against each other to demonstrate that, even in isolation, they form a robust dendrochronological record (Table 2). Samples for ^{14}C dating were measured and marked up (pin-holed) along both the transverse and radial section, then dissected using a steel blade under a binocular microscope. In all, the samples cover 987 calendar years from relative year 772 to 1759. Samples of either 10 or 11 tree rings (years) were obtained. Samples were divided as carefully as possible to align with cell walls on annual ring boundaries, but some small degree of error was unavoidable especially when dealing with very narrow tree rings. On certain occasions, cell walls from adjacent years may be partially included or lost from the 10- or 11-yr separations of wood comprising the final sample. However, the contribution of any such errors is negligible in terms of the average measurement made for any given 10- or 11-yr group of tree rings.

Table 2 Summary crossdating information for the 7 juniper trees (Table 1) employed for samples in Table 3 using raw ring widths (in 1/100s of a mm) (no indexing: the ring-width data for the 7 trees employed will be submitted to the ITRDB on publication of this paper). The values shown with no parentheses are the *t* values calculated based on Baillie and Pilcher (1973), and the *r* value is the Pearson linear correlation coefficient, both as implemented in Corina 1.1 (2007 version—http://dendro.cornell.edu/corina/download.php—of a 2003 release by Ken Harris). The values shown inside the parentheses (*t* value, correlation value, and rings/years compared) are from COFECHA (Holmes 1983; Grissino-Mayer 2001) version 6.06P treating the Gordion data as undated floating series. All trees are *Juniperus excelsa* sp. except GOR-2, which is *Juniperus foetidissima* sp. All samples are from the Midas Mound Tumulus, Gordion, except GOR-161 from the Kızlarkaya Tumulus A (5 km north of Gordion) (Table 1). All samples offer acceptable/good to very good cross-matches with several to almost all other samples. Very similar quality values are obtained in all cases if the ring widths are "indexed"; hence, only the values using raw ring widths are shown.

	GOR-161AB RY737-1599					
GOR-76B	*t* = 11.05 (10.3) *r* = 0.37 (0.35) (RY847-1599)	GOR-76B RY847-1676				
GOR-3A-E	*t* = 8.62 (8.3) *r* = 0.33 (0.32) (RY999-1599)	*t* = 20.26 (19.9) *r* = 0.61 (0.61) (RY999-1676)	GOR-3A-E RY999-1763			
GOR-87ABC	*t* = 8.47 (8.8) *r* = 0.33 (0.34) (RY904-1495)	*t* = 20.77 (18.7) *r* = 0.65 (0.61) (RY904-1495)	*t* = 15.72 (15.4) *r* = 0.58 (0.57) (RY999-1495)	GOR-87A RY904-1495		
GOR-36AE	*t* = 5.83 (7.0) *r* = 0.23 (0.27) (RY993-1599)	*t* = 16.33 (15.8) *r* = 0.54 (0.53) (RY993-1645)	*t* = 18.71 (21.1) *r* = 0.59 (0.64) (RY999-1645)	*t* = 13.22 (15.2) *r* = 0.51 (0.56) (RY993-1495)	GOR-36AE RY993-1645	
GOR-2ABCD	*t* = 5.72 (6.8) *r* = 0.30 (0.36) (RY1279-1599)	*t* = 6.15 (9.6) *r* = 0.3 (0.44) (RY1279-1676)	*t* = 7.90 (12.6) *r* = 0.36 (0.52) (RY1279-1709)	*t* = 5.14 (5.1) *r* = 0.33 (0.33) (RY1279-1495)	*t* = 6.3 (10) *r* = 0.31 (0.46) (RY1279-1645)	GOR-2ABCD RY1279-1709
GOR-83ABC RY1346-1762	*t* = 5.63 (5.6) *r* = 0.33 (0.33) (RY1346-1599)	*t* = 9.99 (10.3) *r* = 0.48 (0.49) (RY1346-1676)	*t* = 12.81 (13.1) *r* = 0.53 (0.54) (RY1346-1762)	*t* = 5.19 (4.7) *r* = 0.39 (0.36) (RY1346-1495)	*t* = 7.19 (8.1) *r* = 0.38 (0.43) (RY1346-1645)	*t* = 5.89 (10.3) *r* = 0.3 (0.48) (RY1346-1709)

Sample pretreatment methods have evolved slightly at the Heidelberg Radiocarbon Laboratory across the period (later 1980s to 2009) relevant to all the measurements. The samples were milled and then pretreated using versions of the AAA sequence; originally as described in Kromer and Becker (1993) and later with 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 $NaClO_2$ to cellulose. The samples were then combusted (since Hd-22720, March 2003 in a Parr bomb), and the CO_2 was purified. The samples were measured for (variously) 7 to 12 days at the Heidelberg Radiocarbon Laboratory low-level gas counters (Kromer and Münnich 1992). The error reported in Table 3 comprises the Poisson counting statistics and regression analyzes of background versus coincident count rate (an indicator of barometric pressure changes) and standard versus gas purity. In all, we report results on 128 juniper samples from the Gordion Area dendrochronology.

RESULTS AND WIGGLE-MATCHING

The ^{14}C age obtained for each of the dated sets of tree rings is provided in Table 3, and the set of 128 ^{14}C data are shown in terms of the relative years of the Gordion Area dendrochonology in Figure 2. The mid-point of each dated set of 10 or 11 tree rings (see Table 3) is used as the reference point for that set (in terms of the calendar-year spacing between samples for wiggle-matching, and for the plotting of the samples in Figures 2, 5, 6, 9, 11).

Table 3 Summary of COFECHA (Holmes 1983; Grissino-Mayer 2001) version 6.06P quality control analysis of the crossdated tree-ring series in Table 2. Spline set at Default (32 yr). The samples cover 1027 yr with 916 yr having 2 or more series (i.e. are capable of comparison) with timespans covered by the samples of (respectively) 863, 830, 765, 592, 653, 431, and 417 yr. We are dealing with long series and in some cases (especially GOR-161) examples where there is relatively weak crossdating or widely separated key crossdating years; thus, use of a longer segment length than the default (of 50 yr) is likely appropriate (Grissino-Mayer 2001:208). We show outputs with the default segment length and lag, and then (as appears appropriate) with use of longer segment lengths. A "flag" indicates a possible problem with the placement of a segment. We believe the crossdatings as stated in Table 2 are secure.

Tree	Interval	Correlation with master	50-yr segments lagged 25 yr nr of flags	100-yr segments lagged 25 yr nr of flags	150-yr segments lagged 25 yr nr of flags
GOR-161AB	737–1599	0.375	11	2	0
GOR-76B	847–1676	0.634	3	0	0
GOR-3A-E	999–1763	0.675	0	0	0
GOR-87A	904–1495	0.644	0	0	0
GOR-36AE	993–1645	0.642	0	0	0
GOR-2ABCD	1279–1709	0.561	1	0	0
GOR-83ABC	1346–1762	0.567	1	0	0
Mean		0.586			

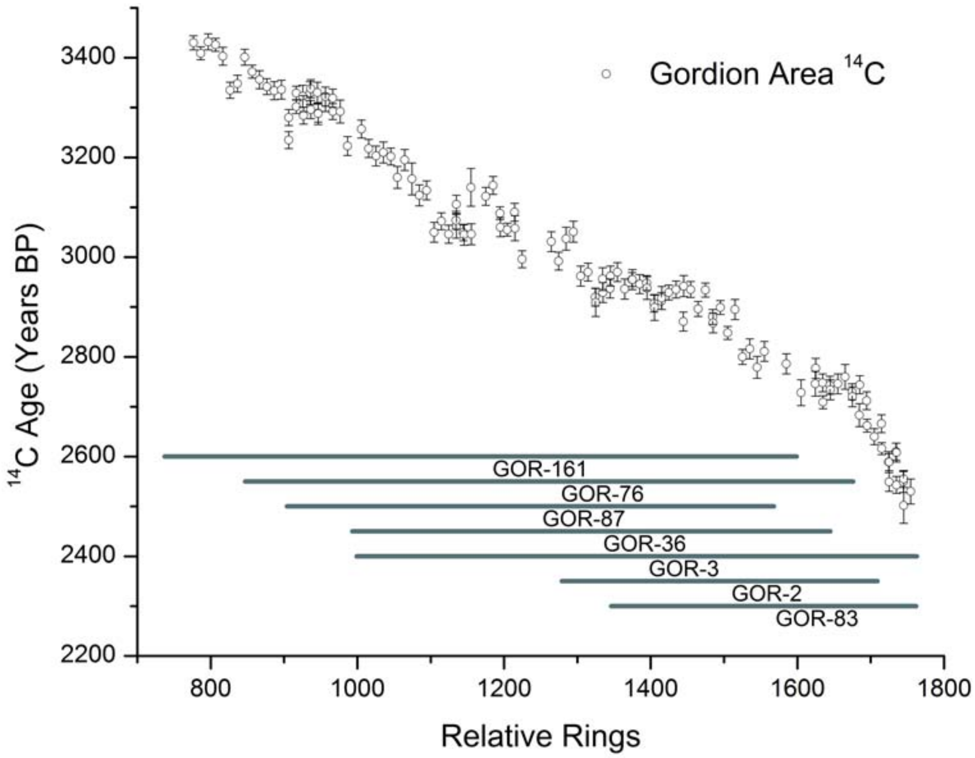

Figure 2 The 128 ^{14}C data from the Gordion Area dendrochronology (Table 3) in terms of the annual tree-ring time series from the relative rings scale. Error bars are 1 σ. The tree-ring periods covered by the 7 trees employed in this study are also shown. Note: some data points are obscured by other data points (also applies in Figures 5 and 11).

The questions we seek to investigate are (i) how the Gordion data compare to the Northern Hemisphere international ^{14}C calibration curve IntCal09 (Reimer et al. 2009), and whether any offsets/ variations are evident; and (ii) what the best calendar date placement of the Gordion data are (against IntCal09), and so the best near-absolute dating of the Gordion Area dendrochronology. The background to this new study is that previous work indicated an apparent offset when studying 2 smaller sets of Gordion ^{14}C data comprising 52 measurements in all (suggested to relate to the exaggeration of growing-season differences at times of major solar minima: Kromer et al. 2001; Manning et al. 2001). We seek to check and better define this topic with a much expanded data set (128 measurements in total; Table 4).

Table 4 ^{14}C measurements from the Heidelberg Radiocarbon Laboratory (analysis number shown) on samples (given by GOR number) from the Gordion Area dendrochronology (see Tables 1–2, and as shown in Figure 2), as of January 2010, $n = 128$. Tree-ring numbers and mid-points given relate to the relative years of the floating Gordion Area dendrochronology. There are some minor differences to data reported previously in some cases; these are because of subsequent revisions to the Heidelberg Laboratory standard/background calculation, and a 1-yr rounding effect that can occur when extracting data from the laboratory database, or correction of a previous data entry error. The measurement errors shown are those determined as the laboratory measurement error; they include no additional error adjustment or multiplier beyond the laboratory counting error (whereas some of the data has previously been reported with what were determined then as the adjusted errors to allow for other unknown factors: Kromer et al. 2001; Manning et al. 2001, 2003).

Center ring	Hd nr	Gordion tree	Start ring	End ring	δ^{13}C (‰)	^{14}C age yr BP	1 SD error
776.5	19793	161	772	781	–21.59	3430	14
786.5	20171	161	782	791	–21.49	3409	13
796.5	19799	161	792	801	–21.63	3432	16
806.5	20160	161	802	811	–21.44	3426	13
816.5	19983	161	812	821	–21.2	3403	18
826.5	19993	161	822	831	–21.49	3335	16
836.5	20163	161	832	841	–20.94	3348	17
846.5	19969	161	842	851	–20.92	3401	16
856.5	20158	161	852	861	–21.66	3372	13
866.5	19982	161	862	871	–21.64	3356	18
876.5	20250	161	872	881	–21.73	3342	16
886.5	19984	161	882	891	–21.54	3334	18
896.5	20251	161	892	901	–21.37	3336	19
906.5	19990	161	902	911	–21.65	3235	17
906.5	24489	76	902	911	–21.98	3280	16
916.5	20252	161	912	921	–21.98	3302	14
916.5	24487	76	912	921	–21.86	3329	14
925.5	26027	161	921	930	–20.77	3323	22
926.5	20134	161	922	931	–22.01	3284	17
926.5	24488	76	922	931	–21.75	3308	16
935.5	26028	161	931	940	–20.66	3329	23
936.5	20137	161	932	941	–21.98	3338	18
936.5	24256	76	932	941	–22.01	3296	18
945.5	26051	161	941	950	–20.27	3330	21
946.5	20135	161	942	951	–21.79	3289	18
946.5	24258	76	942	951	–21.73	3288	22
956.5	20136	161	952	961	–21.9	3310	18
956.5	24257	76	952	961	–21.72	3322	19
966.5	20253	161	962	971	–22.21	3292	16
966.5	24366	76	962	971	–21.95	3319	18
976.5	20623	161	972	981	–22.39	3292	23
986.5	19973	161	982	991	–21.56	3223	19
1005.5	26050	87	1001	1010	–20.52	3257	18
1015.5	26049	87	1011	1020	–20.73	3218	18

Table 4 *(Continued)*

Center ring	Hd nr	Gordion tree	Start ring	End ring	δ^{13}C (‰)	^{14}C age yr BP	1 SD error
1025.5	26069	87	1021	1030	–20.9	3203	20
1035.5	26068	87	1031	1040	–20.71	3210	21
1045.5	26065	87	1041	1050	–20.64	3202	17
1054.5	25786	3	1050	1059	–21.63	3160	22
1064.5	25781	3	1060	1069	–21.8	3195	21
1074.5	25782	3	1070	1079	–22.01	3157	32
1084.5	25769	3	1080	1089	–21.85	3124	21
1094.5	25768	3	1090	1099	–22.01	3134	19
1104.5	25766	3	1100	1109	–22.04	3050	20
1114.5	25748	3	1110	1119	–22.23	3072	17
1124.5	25747	3	1120	1129	–21.8	3046	18
1134.5	25745	3	1130	1139	–21.89	3074	18
1135	21774	3	1130	1140	–22.3	3106	18
1135	21711	161	1130	1140	–21.72	3062	24
1144.5	25723	3	1140	1149	–21.74	3049	16
1145.5	26097	36	1141	1150	–19.59	3045	21
1155	21720	161	1150	1160	–21.5	3140	38
1155.5	26098	36	1151	1160	–19.62	3046	21
1175	21721	161	1170	1180	–21.77	3122	18
1185	21722	161	1180	1190	–21.63	3144	18
1194.5	24558	3	1190	1199	–21.95	3088	13
1195	21761	161	1190	1200	–21.71	3060	19
1204.5	24556	3	1200	1209	–21.96	3055	13
1214.5	24570	3	1210	1219	–22.12	3090	18
1215	21712	161	1210	1220	–21.28	3058	25
1224.5	24559	3	1220	1229	–22.07	2996	17
1264.5	25726	3	1260	1269	–20.33	3031	20
1274.5	25714	3	1270	1279	–22.13	2992	18
1284.5	25708	3	1280	1289	–20.2	3037	23
1294.5	25706	3	1290	1299	–20.47	3051	21
1304.5	25707	3	1300	1309	–20.39	2962	20
1314.5	25681	3	1310	1319	–22.07	2970	18
1324.5	25688	3	1320	1329	–22.06	2920	18
1325	10439	2	1320	1330	–20.92	2909	28
1334.5	25689	3	1330	1339	–20.68	2956	23
1335	10440	2	1330	1340	–20.55	2929	20
1344.5	25661	3	1340	1349	–22.14	2937	19
1345	10441	2	1340	1350	–20.63	2962	20
1354.5	26965	3	1350	1359	–20.21	2970	19
1364.5	26966	3	1360	1369	–20.18	2936	20
1374.5	27000	3	1370	1379	–20.17	2955	14
1375	10460	2	1370	1380	–21.16	2955	20
1385	18586	2	1380	1390	–20.95	2946	19
1394.5	27001	3	1390	1399	–20.02	2948	15
1395	10822	2	1390	1400	–20.75	2938	23
1404.5	27002	3	1400	1409	–19.86	2907	17
1405	10823	2	1400	1410	–20.77	2899	26
1414.5	27005	3	1410	1419	–19.88	2912	17
1415	18788	2	1410	1420	–20.84	2918	23
1424.5	27003	3	1420	1429	–19.81	2929	15
1434.5	27004	3	1430	1439	–20.05	2935	17
1444.5	27017	3	1440	1449	–20.02	2871	19
1445	10461	2	1440	1450	–20.94	2942	21
1454.5	27018	3	1450	1459	–20	2935	16
1464.5	27016	3	1460	1469	–20.04	2896	15

Table 4 *(Continued)*

Center ring	Hd nr	Gordion tree	Start ring	End ring	δ^{13}C (‰)	^{14}C age yr BP	1 SD error
1474.5	27020	3	1470	1479	–20.18	2934	14
1484.5	27021	3	1480	1489	–20.08	2880	15
1485	10473	2	1480	1490	–20.62	2868	20
1495	20958	2	1490	1500	–21.16	2899	14
1505	21044	2	1500	1510	–22.58	2848	13
1515	10480	2	1510	1520	–20.73	2895	20
1525	21043	2	1520	1530	–20.39	2800	15
1535	18587	2	1530	1540	–20.9	2816	20
1545	18863	2	1540	1550	–21.01	2779	22
1555	10502	2	1550	1560	–20.71	2811	20
1585	10688	2	1580	1590	–21.52	2786	20
1605	21083	2	1600	1610	–20.87	2728	26
1624.5	21377	3	1620	1629	–21.88	2746	25
1625	10517	3	1620	1630	–20.25	2777	20
1634.5	21378	3	1630	1639	–22.04	2748	18
1635	20980	2	1630	1640	–20.63	2709	13
1644.5	21322	3	1640	1649	–21.56	2743	18
1645	10518	3	1640	1650	–20.44	2734	20
1655	10533	3	1650	1660	–20.21	2746	20
1665	10542	3	1660	1670	–20.55	2760	25
1674.5	24696	3	1670	1679	–21.69	2730	16
1675	10687	3	1670	1680	–20.19	2720	20
1684.5	24699	3	1680	1689	–21.39	2683	23
1685	24111	3	1680	1690	–21.57	2744	18
1694.5	24697	3	1690	1699	–21.67	2712	18
1695	24055	3	1690	1700	–21.7	2662	13
1705	24075	3	1700	1710	–21.73	2640	16
1714.5	21374	3	1710	1719	–22.36	2666	18
1715	24054	3	1710	1720	–21.68	2616	12
1724.5	21375	3	1720	1729	–22.15	2589	21
1725	24076	3	1720	1730	–21.46	2589	17
1725	24708	83	1720	1730	–22.23	2549	19
1734.5	21320	3	1730	1739	–21.46	2610	17
1735	24074	3	1730	1740	–21.5	2543	17
1735	24705	83	1730	1740	–22.69	2608	19
1744.5	21321	3	1740	1749	–21.33	2549	21
1745	24077	3	1740	1750	–21.41	2555	17
1745	24707	83	1740	1750	–23.34	2502	36
1754.5	21340	3	1750	1759	–21.23	2530	25

Comparison of the Gordion ^{14}C Time Series Versus IntCal09

We compared the floating dendrochronologically sequenced Gordion ^{14}C time series against IntCal09 (Reimer et al. 2009) using the `D_Sequence` function of OxCal 4.1.6 (Bronk Ramsey 1995, 2009a; Bronk Ramsey et al. 2001). The Agreement Index of OxCal (for the series and for the individual data) provides an indication of the quality of fit of the Gordion series against IntCal09. The results of trying a `D_Sequence` analysis are listed in Table 5. Runs 1 and 3 employing all the 128 data against IntCal09 and IntCal98 (Stuiver et al. 1998a), respectively, yield poor overall series agreement values, with numerous individual data also flagged for having poor agreement values. Even adding an allowance for an error multiplier (of 1.19) for the Heidelberg data (see Reimer et al. 2004: Table 1), the series still fail to offer a satisfactory agreement (although only just missing in the case of run 2) and numerous individual data are flagged for having poor agreement values.

Table 5 Best placements of the ^{14}C data (Table 4, Figure 2) given the tree-ring time series against IntCal09 (Reimer et al. 2009) and IntCal98 (Stuiver et al. 1998a) employing the `D_Sequence` function of OxCal 4.1.6 (Bronk Ramsey 1995, 2009a; Bronk Ramsey et al. 2001). Cubic Interpolation was left as Default. Runs 1–4 yield unsatisfactory OxCal agreement index values. Runs 2* and 4* are with a 1.19 error multiplier (after Reimer et al. 2004: Table 1) applied to the Heidelberg data (rounded to nearest whole number). The agreement index rises substantially (to almost satisfactory for Run 2*, and to much higher values for Run 4*), consistent with the view that the stated laboratory error does not represent all the uncertainty involved in the ^{14}C age measurement (see also Kromer et al. 2001:2530). Typical values shown; different runs can yield 0–1 yr variations.

Run	Calibration curve	Curve res.	Relative rings employed	Nr data	Ring 776.5 mean best fit cal BC	Ring 776.5 mode best fit cal BC	68.2% range of fit cal BC	95.4% range of fit cal BC	OxCal A_{comb} value	Nr of dates with individual agreement values <60
1	IntCal04	5	776.5 to 1754.5	128	1737	1738.5	1742–1735	1742–1732	1.2<6.2	32
2*	IntCal04	5	776.5 to 1754.5	128	1737	1738.5	1741–1735	1743–1735	6<6.2	30
3	IntCal98	5	776.5 to 1754.5	128	1738	1738.5	1742–1736	1742–1732	0.7<6.2	28
4*	IntCal98	5	765.5 to 1754.5	128	1737	1736.5	1739–1736	1740–1735	3.9<6.2	26

We therefore conclude that the overall set of 128 dates has some issues involving either or both some outliers or a systematic offset. To investigate the question of a systematic offset, we used the ΔR function of OxCal and considered priors of 0 ± 10 and 0 ± 20 (calendar years) for all 128 data against IntCal09 (Figures 3, 4). It is clear that there is some form of offset in operation, in particular one of ~10 yr (looking at the most likely probability regions) when the data as considered as 1 overall set.

The next question is whether this "offset" applies consistently across the series. To consider the quality/variability within the Gordion data series, we considered an outlier analysis of the 128 date full series using the OxCal `Outlier_Model ("SSimple", N(0,2),0,"s")` with {Outlier, 0.05} (Bronk Ramsey 2009b) against IntCal09. This model is considering any data more than 2× their stated error from the calibration curve as outliers. Results are shown in Figure 5.

Some patterns are noticeable. First, several of the "outliers" are in areas close to major "wiggles" in the IntCal98 curve (largely smoothed away in IntCal09), such as around 1675, 1325, and 1225 BC, and so may reflect real ^{14}C variations. Second, from relative ring 1155 onwards over 599.5 yr, all outliers ($n = 19$) are in one direction: too old ^{14}C ages; whereas the situation is mixed for rings 776.5 to 1145.5 (3 too old, 6 too recent). In particular, the group of 12 data points for relative rings 1175–1294.5 (with 7 "outliers") corresponds in their apparent offset from IntCal09/IntCal04 (Reimer et al. 2009, 2004) with new measurements on known-age German oak showing a similar tendency across this later 14th through 13th century BC period (Kromer et al. 2010; Manning et al. 2009b: Figure 3). Six "outliers" in the 9th–8th centuries BC indicate another apparently real issue, discussed previously: a real short-term regional ^{14}C offset linked to exaggeration of growing-season differences during a major solar minimum (Kromer et al. 2001; Manning et al. 2001). Thus, the attempt of the best-fit analysis to minimize all the differences between IntCal09 and the overall Gordion Area data set may be misguided in the cases of the later 14th–13th centuries BC (where IntCal09/IntCal04 perhaps needs revision) and the 9th–8th centuries BC (where a real small regional offset is likely), and generally for the later part of the data set where all differences are in one direction (which may be reflecting reality, versus random laboratory or other variation). Third, if one looks at the older part of the Gordion Area data (relative rings 776.5–1145.5), it is noticeable that a small shift in the tree-

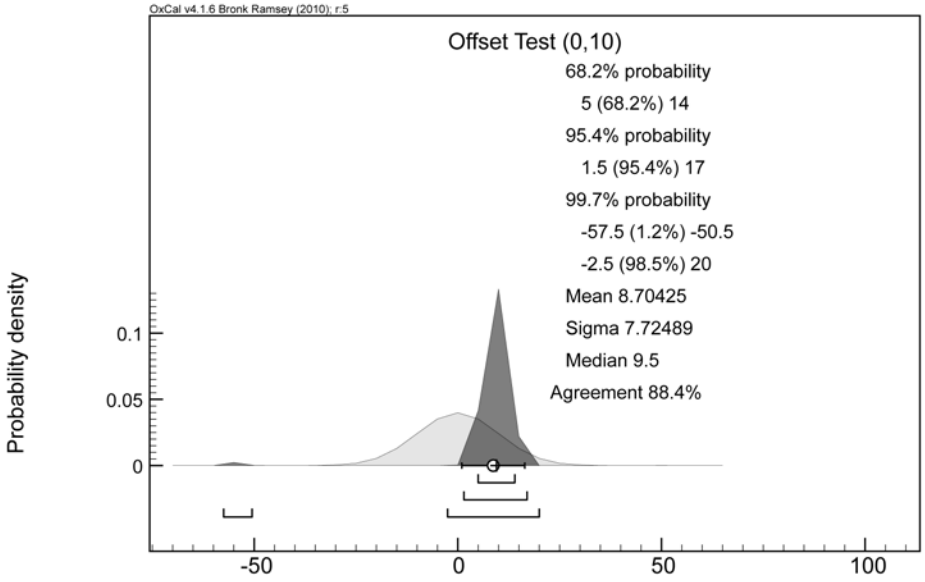

Figure 3 A typical output of a consideration of whether there is a systematic regional offset operating when comparing the full 128 date Gordion data set against IntCal09 (Reimer et al. 2009) (curve resolution 5) using the ΔR function in OxCal with a prior of 0 ± 10 yr (Bronk Ramsey 1995, 2009a,b; Bronk Ramsey et al. 2001). (Note: bibliographic references for IntCal and OxCal are not repeated in subsequent captions.) The answer is "yes," with the main apparent offset mode at 10 yr (median 9.5 yr) within the most likely 68.2% probability region of 5 to 14 yr. There is a very small split probability outcome; while most outcomes from runs of the model are similar to the above, a few choose instead the much less likely older (by ~100 yr) fit as evident in the plot (only 1.2% probability considering the most likely 99.7% probability range). If the prior is increased to 0 ± 20, then this earlier possibility can some few times become a little more likely, but it remains outside the 68.2% most likely range and typically is ~17% of the most likely 95.4% range in most runs of the model: see e.g. Figure 4 (lower). Those few runs that try to favor the earlier fit have almost no constituent data with satisfactory agreement values and we exclude this position as not plausible.

ring/calendar timescale to lower ages (e.g. by ~10 yr) would offer a better fit, in particular, the conspicuous dip in the ^{14}C record about 1600–1595 BC in both IntCal09 and IntCal98 and the immediate reversal would synchronize with the relevant data from the Gordion Area series (data for relative rings 906.5 and then 916.5; 2 measurements for each decade, each showing consistent pattern).

We therefore conclude that the ΔR offset factor observed above is likely not a consistent offset applying over the entire Gordion data series. Instead, it appears that the older part of the Gordion data series (rings centered 776.5 to about rings centered 1145.5) offers a potentially good fit with the IntCal09 calibration record with no indication of anything more than a small systematic offset (see further discussion below), whereas sections of the more recent part of the Gordion data series do appear to exhibit larger offset(s) against IntCal09. We therefore considered the outlier and ΔR performance of the older (rings centered 776.5 to 1145.5) and more recent (rings centered 1155 to 1754.5) parts of the Gordion data series separately in terms of the same outlier model as above, and with a ΔR prior of 0 ± 10 (Figures 6–10). Of course, the exact choices of which rings to include in these "older" and "more recent" sets is arbitrary: the division into the 2 sets (1. older than the decade centered relative ring 1155, and then 2. from the decade centered 1155 and more recent) is "by eye" from Figure 5. Changing the dividing point would modify the findings reported in Figures 6–10 slightly.

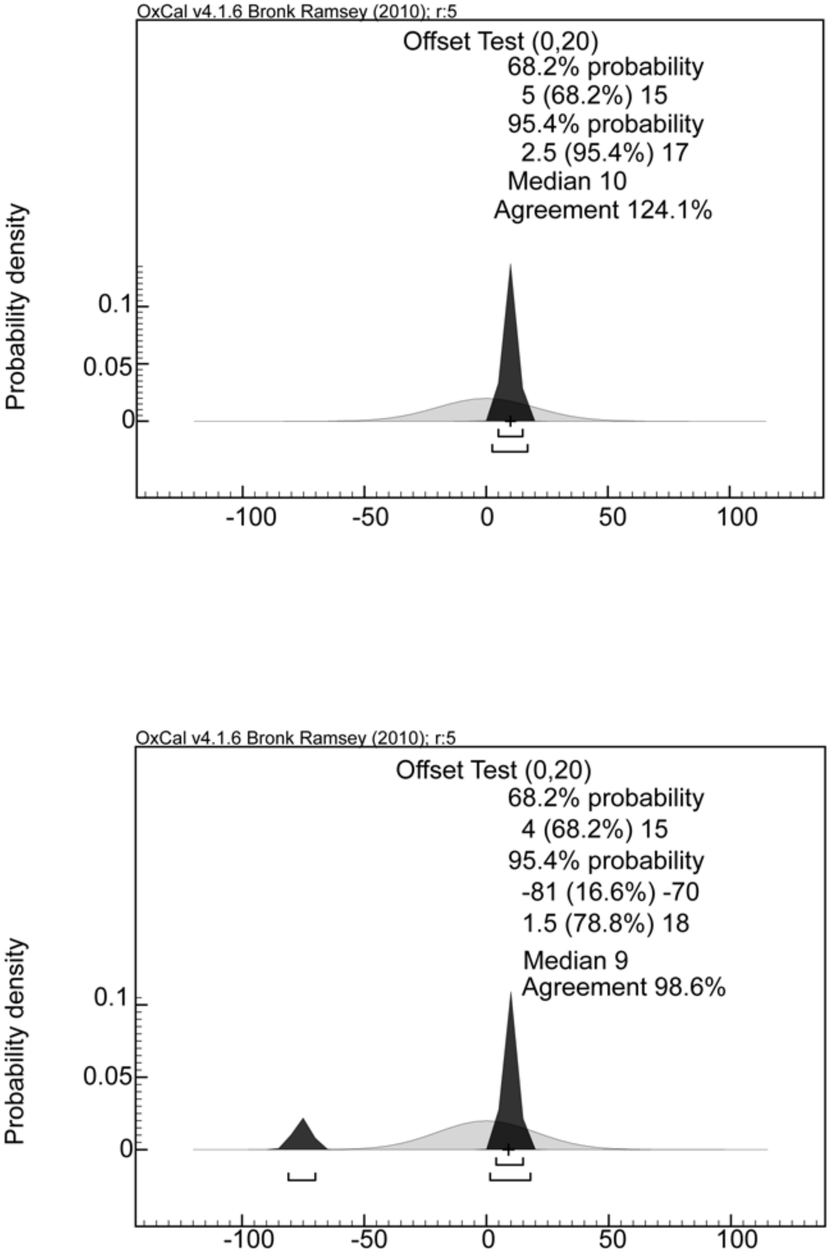

Figure 4 Upper: A typical output of a consideration of whether there is a systematic regional offset operating when comparing the full 128-date Gordion data set against IntCal09 (curve resolution 5) using the ΔR function in OxCal with a prior of 0 ± 20 yr. Compare with the very similar finding in Figure 3. The answer is "yes" with the main apparent offset mode at 10 yr (median 10 yr also) within the most likely 68.2% probability region of 5 to 15 yr. Lower: In some runs of the model, there is a small split probability outcome (compare with Figure 3). While most outcomes from runs of the model are similar to the Figure 3 or Figure 4 Upper plots, a few runs give a larger (but small) probability to an older fit with this Lower plot showing such an example. But this older fit option remains outside the 68.2% most likely range and typically is ~17% of the most likely 95.4% range in numerous runs of the model—and we note that the convergence is poor in these runs (and the model is very slow to converge). Those very few runs that try to favor the earlier fit more strongly have almost no constituent data with satisfactory agreement values, and we exclude this position as not plausible.

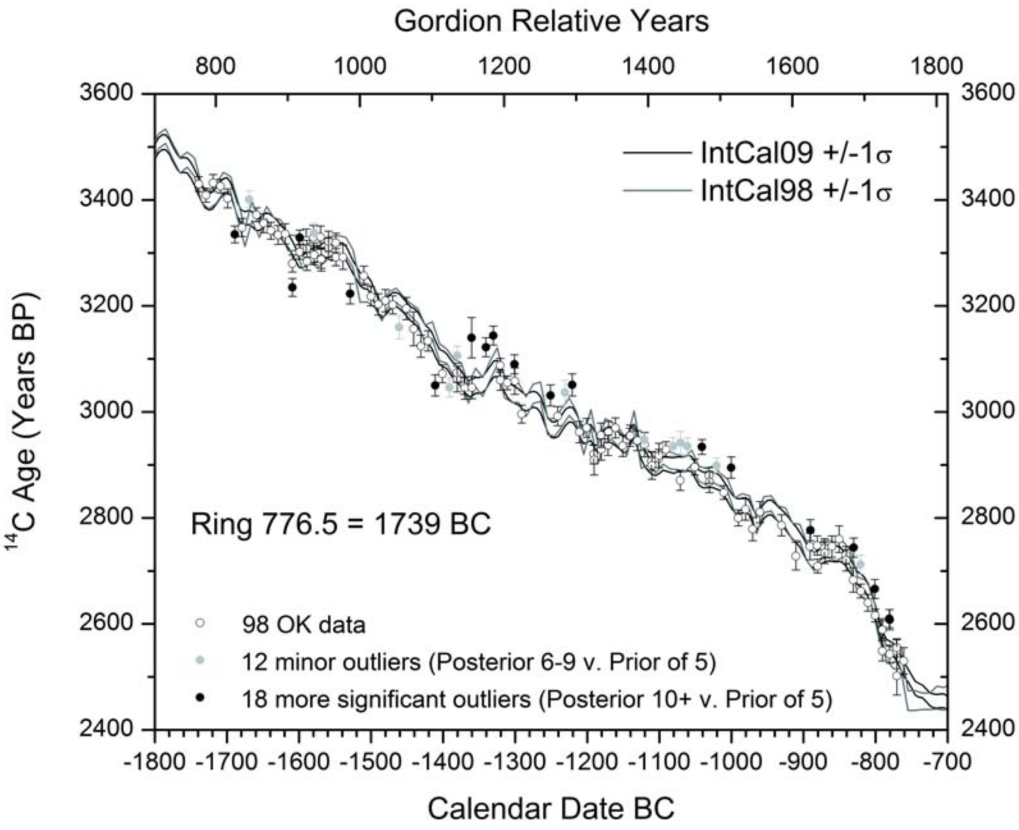

Figure 5 The Gordion Area ^{14}C data shown in Figure 2 (from Table 4) as best-fitted against the IntCal09 ^{14}C calibration curves on the basis of all 128 data (curve resolution 5). The IntCal98 calibration curve is also shown. Those samples found to be outliers using `Outlier_Model ("SSimple", N(0,2),0,"s")` with `{Outlier, 0.05}` (Bronk Ramsey 2009b) against IntCal09 (those where the dates are more than 2× their measurement errors from the calibration curve; thus, the calculated posterior value is greater than the Prior of 5) are indicated. Minor outliers (subjectively deemed as those with a posterior value <10) and more significant outliers (subjectively deemed to be those with posteriors >10) are indicated. Note all outliers from ring 1155 onwards (to the right in the figure) are in the same direction, that is, above (older ^{14}C ages) than the calibration curve. Error bars 1 σ.

Examination of the analyses reported in Figures 6–8 further supports the observations made above. We may observe that the older 50-date Gordion set by itself agrees well with IntCal09 and especially well (effectively 0 offset) with IntCal98 (which has largely similar tree-ring data compared to IntCal04/09 for this period, but a less smoothed calibration curve): similar to the observations made previously on a much smaller data set (Kromer et al. 2001; Manning et al. 2001). In contrast, the more recent 78-date Gordion data set agrees noticeably less well, and in particular all the outliers are in one direction. They also concentrate in 3 distinct temporal periods (see Figure 10 and see further discussion below).

Best Calendar Date Placement of the Gordion ^{14}C Series and Gordion Area Dendrochronology

In light of the observations in the previous section, we therefore consider a best-fit ("wiggle-match") calendar dating of the Gordion Area dendrochronology should be based (only) on the older part of the Gordion Area ^{14}C data, centered relative rings 776.5 to 1145.5 as shown in Figures 6–8. We consider the fits against both IntCal09 and IntCal98 and with and without the error multiplier (Table 6).

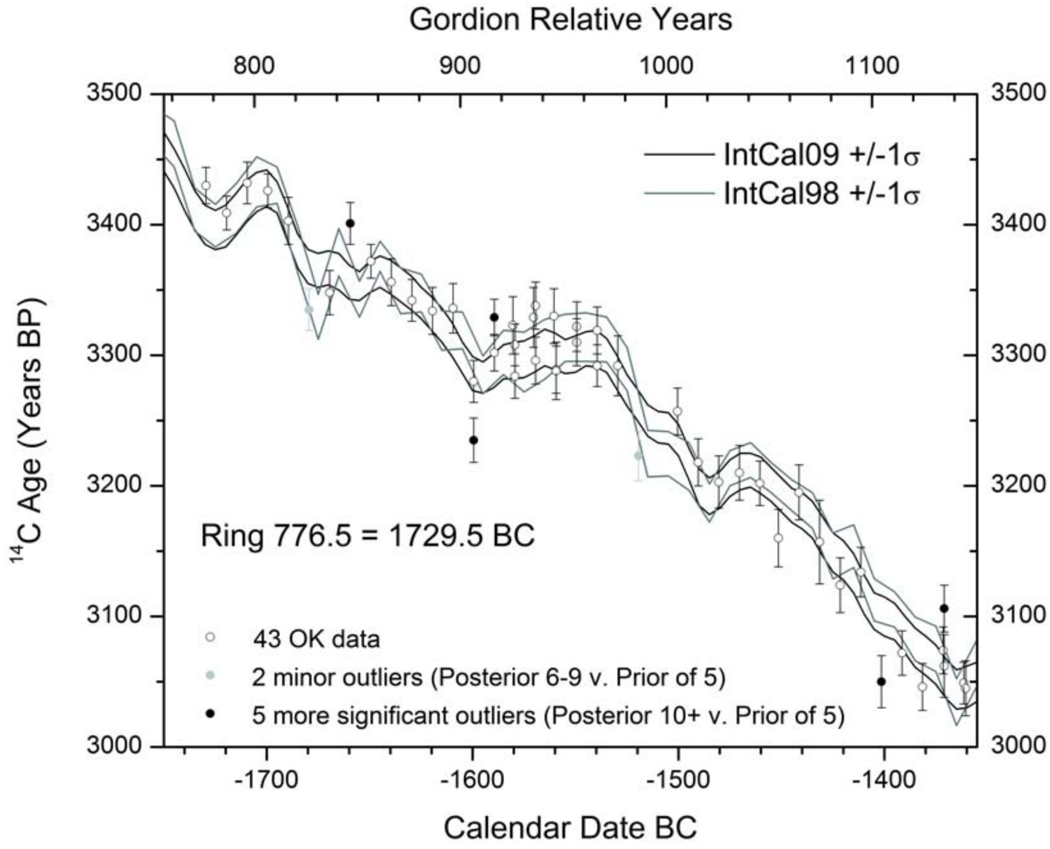

Figure 6 Wiggle-match fit (`D_Sequence`) for the older set of Gordion data (see text for discussion) centered relative rings 776.5 to 1145.5 against IntCal09 using OxCal, *n* = 50. Only 7 data (14%) are outliers applying the `Outlier_Model ("SSimple", N(0,2),0,"s")` with `{Outlier, 0.05}` (Bronk Ramsey 2009b) against IntCal09 (curve resolution 5) as in Figure 5, and only 5 (10%) in a more substantive way. The quality of the data fit is much better than for the overall data set (contrast with Figure 5). The fit range for the mid-point of the first dated decade (ring 776.5) is 1733–1726 BC at 68.2% confidence and 1738–1722 BC at 95.4% confidence (mean 1729 ± 3 BC, median 1730 BC, mode 1729.5 BC; as shown in the plot above). Error bars 1 σ.

This produces in round terms a best-fit ~10 yr later than the initial fit (shown in Figure 5)—we use relative ring 776.5 = 1729 BC as the best estimate and show the revised calendar placement in Figure 11. Although this placement is a relatively minor shift from the position in Figure 5, we consider that this fit is in fact likely to best reflect the correct calendar position of the overall Gordion Area tree-ring time series (as argued previously: Kromer et al. 2001; Manning et al. 2001, 2003). The best fit here is within the range (1730–1728 BC) found in Manning et al. (2003) and just 1–2 yr from the best-fit range (1728–1727 BC) found in Manning et al. (2001), both these analyzes employing IntCal98—which favors a very slightly lower (by 1–2 yr) best fit compared with IntCal09 (see Table 6). If we consider the average of the spread of 95.4% confidence ranges in Table 6 around the mode/best-fit value, we might offer a (highly) conservative, all inclusive, 95.4% level estimate of the error limits (versus likelihood) on this best-fit placement as about +5.69/–7.44 calendar years, which we term +6/–8 yr. The 68.2% error limit on the same basis is about +3.3/–2.7 calendar years.

The raw ^{14}C data in the IntCal09 database (Reimer et al. 2009) are expressed in terms of single whole calendar years. However, in the period 1800–600 BC the samples were run mostly on 10-yr

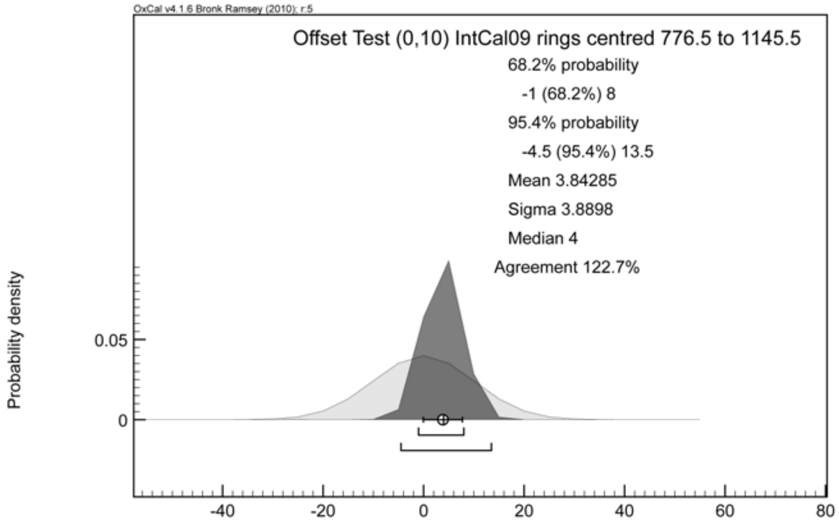

Figure 7 A typical output of a consideration of whether there is a systematic regional offset operating when comparing the older 50-date Gordion data set (rings centered 776.5 to 1145.5) against IntCal09 (curve resolution 5) using the ΔR function in OxCal with a prior of 0 ± 10 yr. A much smaller apparent offset (around 4 yr) is found compared to the whole data set (compare Figures 3 and 4), or when compared to the more recent part of the data set (compare Figure 10). And, as shown in Figure 8, this offset becomes in effect 0 against the older more ragged IntCal98 calibration curve where largely the same (underlying) ^{14}C data are less smoothed to produce the final calibration curve in this time period. Thus, the older Gordion data set seems to have in real terms no substantive, or even no, offset against the Northern Hemisphere calibration curve—in contrast to the more recent part of the Gordion data set (see Figure 10).

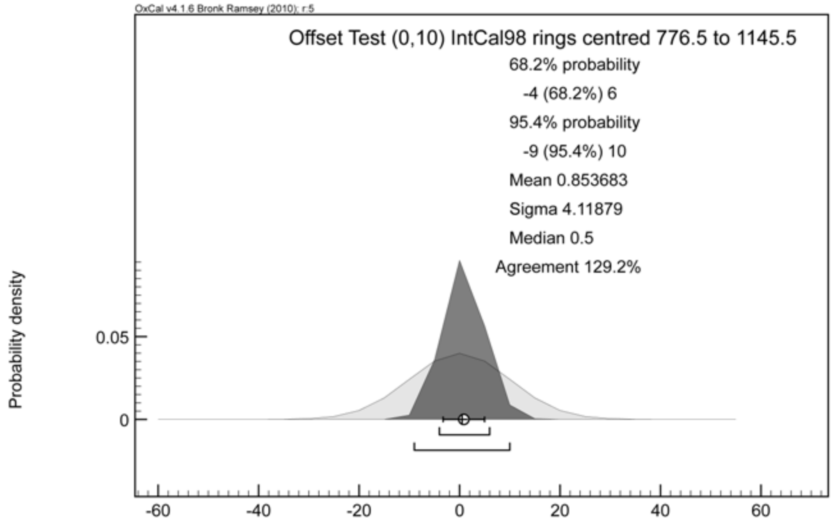

Figure 8 A typical output of a consideration of whether there is a systematic regional offset operating when comparing the older 50-date Gordion data set (rings centered 776.5 to 1145.5) against IntCal98 (curve resolution 5) using the ΔR function in OxCal with a prior of 0 ± 10 yr. No real offset (i.e. one of <1 yr) is found when comparing the older Gordion data against the more ragged IntCal98 calibration curve where largely the same ^{14}C data as in IntCal09 are less smoothed to produce the final calibration curve for this time period. The older Gordion data set seems to have no substantive offset against the Northern Hemisphere calibration curve—in contrast to the more recent part of the Gordion data set (see Figure 10). The best-fit point for the first dated decade (ring 776.5) against IntCal98 is the almost the same as for IntCal09, varying by no more than 1 yr: mean 1728 ± 3 BC, median 1729 BC, mode 1729.5 BC.

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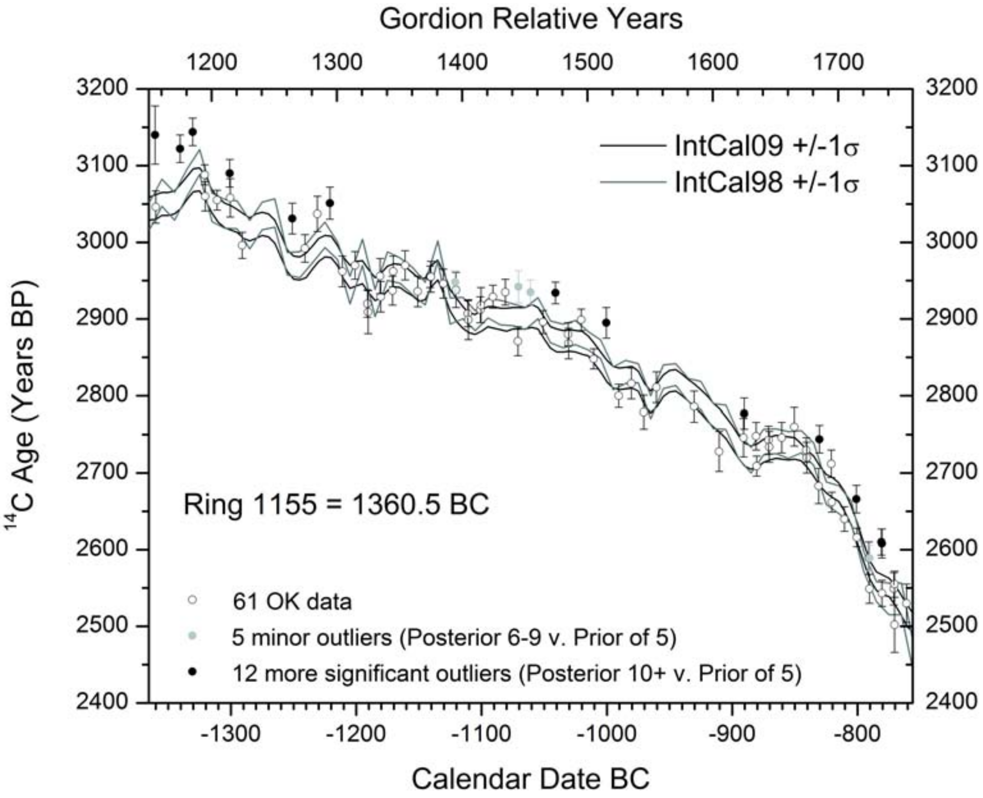

Figure 9 Wiggle-match fit (`D_Sequence`) for the more recent set of Gordion data (see text for discussion) centered relative rings 1155 to 1754.5 against IntCal09 using OxCal, *n* = 78. Seventeen data (21.8%) are outliers applying the `Outlier_Model ("SSimple", N(0,2),0,"s")` with `{Outlier, 0.05}` (Bronk Ramsey 2009b) against IntCal09 (curve resolution 5) as in Figure 5, 12 (15.4%) in a more substantive way. All outliers are in the same direction: older ^{14}C ages. Some apparent groupings are also evident: (i) a group of 6 outliers ~1360–1220 BC among 14 data (with 5 of the 8 other data also tending towards older ^{14}C ages than IntCal09); (ii) a group of 5 outliers out of 13 data 830–780 BC; and (iii) perhaps a partial grouping about 1070–1000 BC. The fit range for the mid-point of the first dated decade (ring 1155) is 1364–1359 BC at 68.2% confidence and 1368–1357 BC at 95.4% confidence (mean 1362 ± 2 BC, median 1362 BC, mode 1360.5 BC; as shown in the plot above). Error bars 1 σ.

and some 20-yr sections of wood and thus the mid-points of the dated samples will have usually been between year 5 and year 6 of the relevant decade (years 1–10) of wood (hence the ...*x*.5 in the ring descriptions in 10-yr sections), or between years 10 and 11 (of 1–20). For example, the Belfast data are placed as years BC *xxx*0, which implies a rounding down by up to "half" a year (see also Pearson and Stuiver 1986), and the Seattle data originally reported in the relevant period as *xxx*6.5 (Stuiver and Becker 1986) were published as *xxx*7 (Stuiver et al. 1998b), indicating a subsequent rounding up of "half" a year for the IntCal98 calibration curve. In the 2001 studies on the Gordion Area data (Kromer et al. 2001; Manning et al. 2001), the rings were rounded up by "half" a year. There is no entirely satisfactory correlation as the various IntCal data in the relevant period have then been transformed into values for years ending *xxx*5 (IntCal98) or *xxx*0 and *xxx*5 (IntCal04, IntCal09), and all in all we may assume at least a 0–1 yr "error" has become included (and how the transition from 1 BC to AD 1—i.e. the presence or absence of a year 0— has, or has not, been dealt with in long tree-ring series is another issue of the same magnitude and has not been made explicit in these cases). For a best estimation here, we note that an annual growth ring in juniper from the

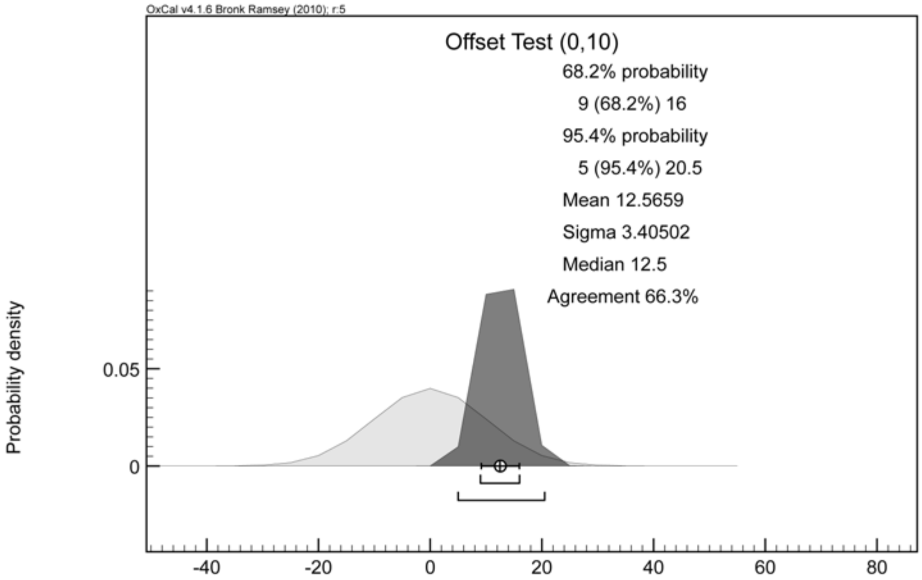

Figure 10 A typical output of a consideration of whether there is a systematic regional offset operating when comparing the more recent 78-date Gordion data set (rings centered 1155 to 1754.5) against IntCal09 (curve resolution 5)—as in Figure 9—using the ΔR function in OxCal with a prior of 0 ± 10 yr. An offset of ~12 yr is evident. The center of the first decade (ring 1155) is placed: mean 1359 ± 2 BC, median 1360 BC, and mode 1360 BC (the last just 0.5 yr different to the placement shown in Figure 9). It is a poor quality fit. The OxCal A_{comb} value is 8 = the minimum A_n value of 8, but A_{model} is 6.3 < 60 and $A_{overall}$ is 5.7 < 60 and 21 (26.9%) of the 78 individual data have OxCal agreement values of <60.

Table 6 Best placements of the Gordion ^{14}C data (Table 4, Figure 2) for rings centered 776.5 to 1145.5 given the tree-ring time series against IntCal09 (Reimer et al. 2009) and IntCal98 (Stuiver et al. 1998a) employing the `D_Sequence` function of OxCal 4.1.6 (Bronk Ramsey 1995, 2009a; Bronk Ramsey et al. 2001). Cubic Interpolation was left as Default. All runs yield satisfactory OxCal agreement index values. Runs E*, F*, I*, and J* are with a 1.19 error multiplier (after Reimer et al. 2004: Table 1) applied to the Heidelberg data (rounded to nearest whole number). The agreement index rises substantially, consistent with the view that the stated laboratory error does not represent all the uncertainty involved in the ^{14}C age measurement (see also Kromer et al. 2001:2530). Typical values are shown; different runs can yield 0–1 yr variations. Runs G, H, I*, and J* exclude the data with individual agreement index values <60 in runs A and B, respectively. All runs yield more or less the same fit: mode or peak fit 1727.5 to 1730 BC (average: 1728.94 BC).

Run	Calibration curve	Curve res.	Relative rings employed	Nr data	Ring 776.5 mean best fit cal BC	Ring 776.5 mode best fit cal BC	68.2% range of fit cal BC	95.4% range of fit cal BC	OxCal A_{comb} value	Nr of dates with individual agreement values <60
A	IntCal09	5	776.5 to 1145.5	50	1730	1729.5	1735–1725	1740–1719	34.1	8
B	IntCal98	5	776.5 to 1145.5	50	1728	1729.5	1733–1725	1735–1711	36.8	6
E*	IntCal09	5	776.5 to 1145.5	50	1725	1729.5	1734–1725	1736–1724	61.3	7
F*	IntCal98	5	776.5 to 1145.5	50	1728	1728.5	1730–1727	1732–1723	63.6	5
G	IntCal09	1	776.5 to 1145.5	42	1731	1730.5–1729.5	1733–1728	1736–1725	191	0
H	IntCal98	1	776.5 to 1145.5	44	1728	1727.5	1730–1726	1731–1723	152.5	4
I*	IntCal09	1	776.5 to 1145.5	42	1731	1729.5	1733–1728	1736–1725	244.6	0
J*	IntCal98	1	776.5 to 1145.5	44	1727	1727.5	1730–1726	1731–1722	193.4	0

Gordion region is likely to represent spring to summer growth. So the nominal ring 776.5 "date" roughly lies somewhere from the later part of ring 776 (later summer) to before the start of growth of ring 777 (so: altogether later summer through autumn/fall to winter, and before the next spring). The wiggle-match thus more relates to placing the calendar year of relative ring 776, and so, as an approximation, we will state that relative year (ring) 776 = 1729 BC with a 0–1 yr error either way (and within an overall 95.4% error limit of +6/–8 calendar years).

Pending further revision to the IntCal09 data set in the 2nd and 1st millennia BC (both new data: e.g. Kromer et al. 2010; and refinements of curve modeling: e.g. Blackwell and Buck 2008; Heaton et al. 2009), the relative year (ring) 776 = 1729 BC placement means that dates previously expressed in terms of the Manning et al. (2001) dates from a wiggle-match against IntCal98, where ring 777 = 1727 BC (+4/–7 yr), should now be approximately 1 ± 1 yr older (and now +6/–8 yr overall within approximate 95.4% confidence limits). (Against IntCal98 with a 1-yr curve modeling as employed in Manning et al. [2001], the older Gordion series offers the same fit within 0.5 yr as the Manning et al. [2001] analysis: see Table 6 runs H and J*.) Since this is a trivial difference, we do not propose any systematic restatement here of dates given previously under the 2001 scheme. We instead highlight that repeated and numerous measurements yield a pretty robust best placement, and that the Gordion Area dendrochronology placement with relative year (ring) 776 = 1729 BC is thus, within the uncertainties noted above, likely a robust near-absolute date.

AEGEAN, GROWING-SEASON-RELATED, ^{14}C OFFSET (LATE 18TH TO 14TH CENTURIES BC, AND ON AVERAGE)

The analysis of the older 50-date Gordion data set (Figures 6–8) indicates a possible systematic offset of ~4 yr (IntCal09) or 0 yr (IntCal98). Analysis of the Miletos oak data set (7 pairs of data) against IntCal09 also yields about a 4-yr offset (Figures 11, 12). Such a very small scale of apparent offset—assumed to relate to slightly offset growing seasons for the Anatolian samples versus those for the "average" IntCal09 samples (German oak, mainly, and Irish oak for this period)—might be assumed to be typical for the Aegean/Anatolia region for periods where either (i) there is not a likely issue/problem with the IntCal09 data set (something we suggest applies in the mid-14th to mid-13th centuries BC: see below), or (ii) a major solar minimum (or other factor on such a scale) applies and exaggerates the usual growing-season offset (something we suggest is relevant to the 9th–8th centuries BC: see below). For further evidence with regard to this topic, we may consider ^{14}C data on known-age Turkish pine (*Pinus nigra*) from Çatacık in western central Anatolia for the pre-modern (pre-industrial) period between AD 1300–1800: Figure 13, Upper (data in Table 7). Analysis of this 5-century data set against IntCal09 with ΔR prior of 0 ± 10 indicates overall only a very small offset of typically about 1.15 ± 2.33 yr (Figure 13, Lower). For some shorter periods, a slightly larger offset is evident, such as a reversal of the usual pattern between the Turkish pine and IntCal09 in the later 15th century BC (and generally through to just after AD 1600)—as discussed in Kromer et al. (2001)—but the overall 5-century comparison indicates a very small general offset <2 yr. In light of the available evidence, we may consider such an offset range of 0–4 yr as typical for the main Aegean/Anatolian region unless other (shorter-term) factors apply (as i and ii above). This scale of offset seems plausible, since the respective "spring-summer" growing seasons in the main Aegean region are only partly offset versus central Europe or Ireland, in contrast to the almost half-year growing season offset when considering pre-modern (i.e. pre-dam) Egypt and its (then) hydrological cycle with the growing season beginning after the summer flood (thus flood and sowing in summer to early autumn and harvest in late winter to spring: Krauss 2006:369–74), where a larger (19 ± 5 yr) offset has been found (Dee et al. 2010).

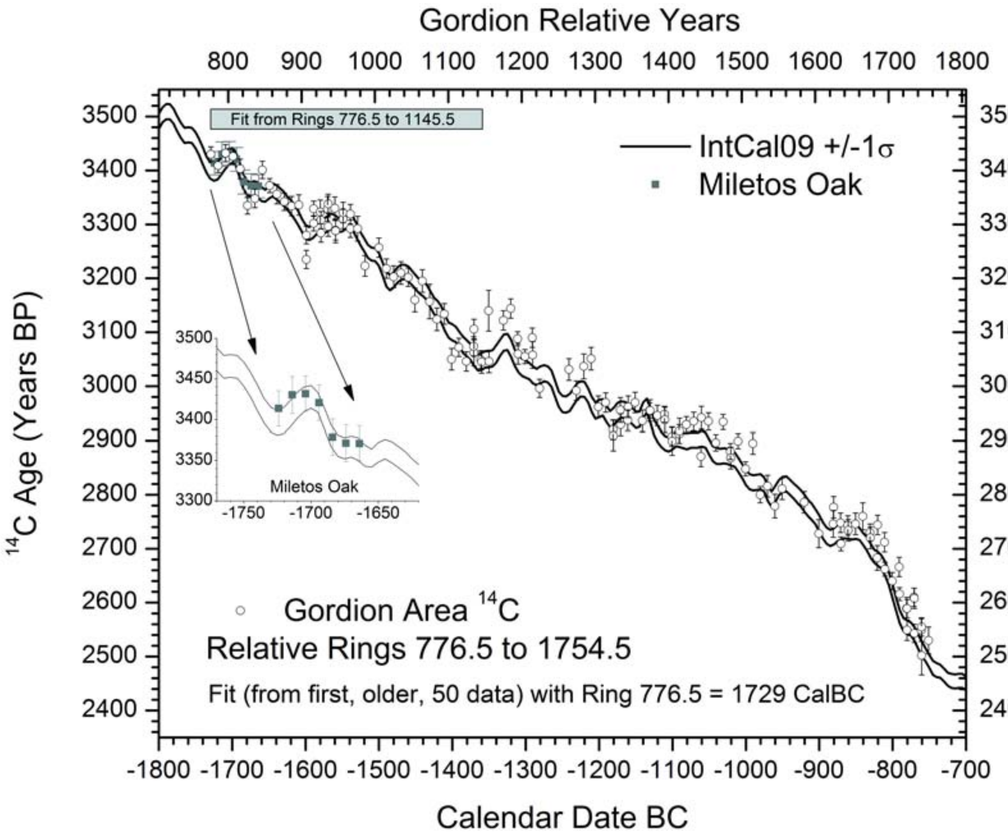

Figure 11 The Gordion Area ^{14}C data (see Figure 2 and Table 4) shown best-fitted against the IntCal09 calibration curve on the basis of the analysis of the older 50 dates in the series (see text and Table 6). An "average" best-fit value of 1729 BC is used (see Table 6). The wiggle-match fit against IntCal09 of the weighted average of 2 ^{14}C measurements on each of seven 11-yr samples (relative rings 1000–1010, 1010–1020 … 1060–1070) from 71 rings/years of an oak sample from Miletos, western Turkey (Bronk Ramsey et al. 2004; Galimberti et al. 2004; Manning et al. 2006) is also shown (see also Figure 12). Error bars 1 σ.

What difference does such a possible minor offset make? One option is to regard any real offset for Aegean material in "typical" circumstances, such as in the late 18th to earlier 14th centuries BC, as inconsequential (which could be argued to be the case employing IntCal98). The other option is to consider whether a potential offset on the order of 2–4 yr or so affects any major dating issues. The reality of such a minor offset is also more likely in the southern Aegean where spring growth starts earlier and the growing-season offset is more likely slightly exaggerated (compared to the Anatolian plateau region). We might consider an offset of 4 ± 4 yr, as in Figure 7 (rather than the smaller value from the AD 1300–1800 comparison, and in preference to the looser 4 ± 8 in Figure 12 since the former is based on a much larger data set and so the standard deviation is likely more realistic), and also a hypothetical "largest likely seasonal offset" value of about 9 ± 4 yr as (i) halfway between the IntCal vs. Egypt offset (Dee et al. 2010), and (ii) roughly double the offset identified for central Anatolia in typical time periods (using same standard deviation of ±4 as found above). (Note: another alternative strategy is to consider a calibration curve based just on wood from the Aegean region and, despite a less defined curve since the density of data is less than for the IntCal09 data set, to explore resultant post-calibration differences. This route is investigated in Manning and Kromer [2010] with regard to the period 1730–1480 BC.)

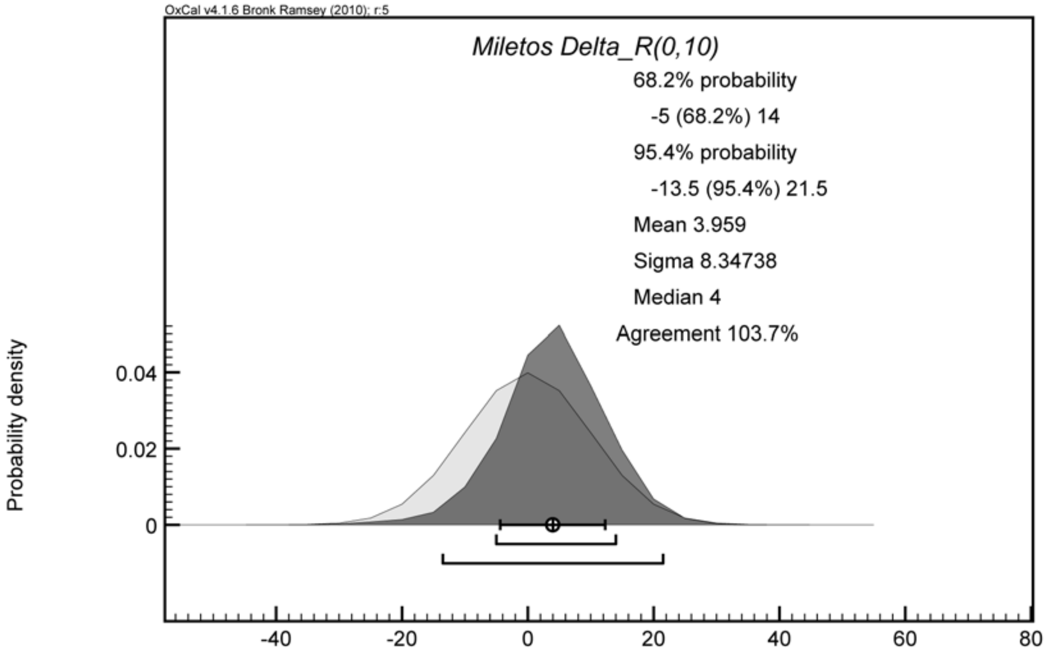

Figure 12 A typical output of a consideration of whether there is a systematic regional offset operating when comparing the Miletos data set (see Figure 11) against IntCal09 (curve resolution 5) using the ΔR function in OxCal with a prior of 0 ± 10 yr. A very small apparent offset (~4 yr) is found—compare the almost identical finding in Figure 7 above. (In this case, similar findings—mean and median of ~4—are also found with IntCal98.)

The much-debated and high-precision case that comes to mind for an investigation and test of the significance (or not) of such offsets is the dating of the Santorini/Thera eruption, whether on the basis of the outer growth portion of an olive branch found in the Plinian pumice deposits from the eruption (Friedrich et al. 2006)—see Figure 14 and caption—or on the basis of the short-lived material from the volcanic destruction level on the island and especially at the archaeological site of Akrotiri (Manning et al. 2006): see Figure 15. The respective ΔR adjustments (0, 4 ± 4, 9 ± 4) very slightly modify (make slightly more recent) the calendar age ranges found on analysis, but these offsets do not make any substantive change to the date ranges found previously (with no offsets): see Table 8. (Previous work has also indicated that the Aegean Late Minoan I–II ^{14}C chronology is fairly robust to any plausible "largest likely seasonal offset" adjustments for various possible issues: Manning and Bronk Ramsey 2003:125–8; Manning et al. 2009a.) The conclusion is that likely growing-season-related regional offsets in the range of 0 to 4 yr, even 0–10 yr (±4 or ±5), have only small effects on data-rich ^{14}C sequence analyses. (We may note that the study of Dee et al. [2010] found that the "impact of this uplift is almost imperceptible" (p 689), even when considering the rather larger, 19 ± 5 yr, offset they applied to the special case of pre-modern Egypt.) To take just one other example, if we consider the ^{14}C data sequences for Iron Age Israel employed by Mazar and Bronk Ramsey (2008), e.g. their Sequence C2 (which they consider the most realistic: p 175), then the application of a ΔR factor of 10 ± 5 yr (arbitrary choice) changes the dates determined for the Iron I/Iron II Boundary by ≤5 calendar years across several runs of this model (e.g. 68.2% range changes from 961–942 BC to, with ΔR of 10 ± 5 yr, 961–939 BC).

The empirical evidence for at most a very modest typical Aegean/Anatolian offset, and even the plausible "largest likely seasonal offset" scenario (still a small offset of <10 yr), all fail to provide

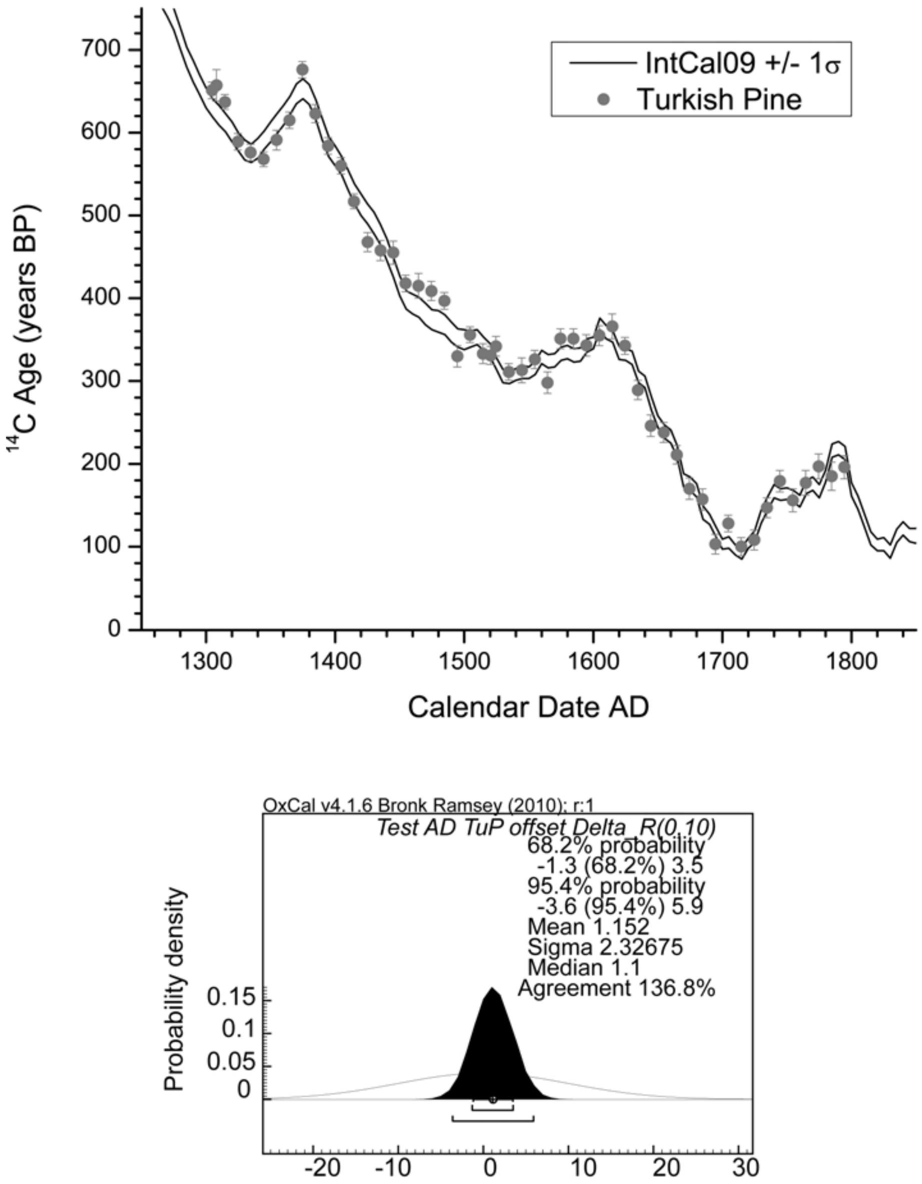

Figure 13 Upper: ^{14}C data on decadal sections of known-age Turkish pine (*Pinus nigra*) from Çatacık in western Anatolia for the pre-modern (pre-industrial) period between AD 1300–1800 ($n = 52$) plotted against the IntCal09 calibration curve. ^{14}C measurements run at the Heidelberg Radiocarbon Laboratory and include data employed previously (e.g. Kromer et al. 2001). Data shown are listed in Table 7. Lower: A typical output of a consideration of whether there is a systematic regional offset operating when comparing the known-age Turkish pine data set between AD1300–1800 against IntCal09 (curve resolution 1) using the ΔR function in OxCal with a prior of 0 ± 10 yr. Only a very small apparent offset (1.15 ± 2.33 yr in the example shown) is found for the overall set (this is 1.07 ± 2.75 with curve resolution 5 in a typical example). With all 52 data, the analysis just fails to yield a satisfactory OxCal A_{comb} value (44.9 < 60). If we apply an `Outlier_Model (“SSimple”, N(0,2),0,”s”)` with `{Outlier, 0.05}` (Bronk Ramsey 2009b) against IntCal09, then 2 data points (samples centered AD 1425.5 and 1644.5) have posteriors >10 (twice the threshold value of 5). If we exclude these, then the A_{comb} value becomes 67.4 > 60 and the mean offset is (typical example) 1.69 ± 2.3.

Table 7 ^{14}C data on decadal sections of known-age Turkish pine (*Pinus nigra*) from Çatacık in western Anatolia for the pre-modern (pre-industrial) period between AD 1300–1800 (*n* = 52) as plotted against the IntCal09 radiocarbon calibration curve in Figure 13 Upper. The ^{14}C measurements were run at the Heidelberg Radiocarbon Laboratory; they include data employed previously and methods described/referenced previously (e.g. Kromer et al. 2001; Manning et al. 2003, 2005). Data came from trees/sections 1, 6, and 15. The tree-ring measurements for these samples (Eskisehir Catacik Orman) are available from the International Tree-Ring Data Bank (ITRDB) at http://www.ncdc.noaa.gov/paleo/treering.html. Note: some small revisions have been made to previously used/published values for some of the data points based on a 2010 recalculation of ages based on the final set of counter parameters at Heidelberg (subsequent revisions to the Heidelberg Laboratory standard/background calculation, 1-yr rounding effect, which can occur when extracting data from the laboratory database, correction of previous data entry). The measurement errors shown are those determined as the laboratory measurement error; they include no additional error adjustment or multiplier beyond the laboratory counting error (whereas some of the data has previously been reported with what were determined then as the adjusted errors to allow for other unknown factors: Kromer et al. 2001; Manning et al. 2001, 2003). The data affected are marked by an * in the table.

Center ring	Hd nr	^{14}C age yr BP	1 SD Error	Center ring	Hd nr	^{14}C age yr BP	1 SD error
1304.5	22611	651	10	1544.5	19537	313	15
1308	22810	657	19	1554.5	19580	326	11
1314.5	22618	637	9	1564.5	19521	298	13
1324.5	22619	589	10	1574.5	19549	351	12
1334.5	22620	576	10	1584.5	19583	351	12
1344.5	22621	568	9	1594.5	19551	343	13
1354.5	22622	591	12	1604.5	21244+19550	356*	10.3
1364.5	22623	615	10	1614.5	19601	366	15
1374.5	22648	676	10	1624.5	21349+19586	342*	10.8
1384.5	22650	623	11	1634.5	20982+19563	289.1	11.7
1394.5	22671	584	10	1644.5	19597	246	13
1404.5	22672	560	10	1654.5	22674	238	12
1414.5	22673	517	9	1664.5	22726	211	11
1425	21088+19972	463*	9.1	1674.5	22723	170	13
1435	20892+19974	452*	8.8	1684.5	22755	157	13
1445	19970	455	14	1694.5	22759	103	12
1454.5	21157+19506	406*	9.2	1704.5	22783	128	10
1464.5	19576	415	15	1714.5	22728	100	11
1474.5	21245+19506	404*	9.8	1724.5	22784	108	12
1484.5	21246+19505	396*	10.5	1734.5	22785	147	12
1494.5	19481	330	13	1744.5	22786	179	13
1504.5	21178+19482	354*	8.1	1754.5	22791	156	14
1514.5	19483	333	12	1764.5	22753	177	15
1520.5	24695	331	11	1774.5	22758	197	15
1524.5	19508	342	12	1784.5	22792	185	17
1534.5	21243+19499	304*	8.6	1794.5	22797	196	14

any grounds to explain the large difference between ^{14}C-based dates and chronologies for the mid-2nd millennium BC Aegean world (e.g. Manning 1999; Kutschera and Stadler 2000; Bronk Ramsey et al. 2004; Friedrich et al. 2006; Manning et al. 2006, 2009a; Wild et al. 2010), versus the much later calendar date estimates made by some archaeologists and art historians based on the traditional/conventional interpretation of comparisons of artifact or stylistic linkages between the Aegean, the east Mediterranean, Egypt, and the Near East (e.g. Warren and Hankey 1989; Bietak 2003; Bietak and Höflmayer 2007; Wiener 2003, 2006; Bruins 2010; Note: Warburton 2009a offers a recent collection of papers which contrasts ^{14}C-based studies versus alternative/critical viewpoints

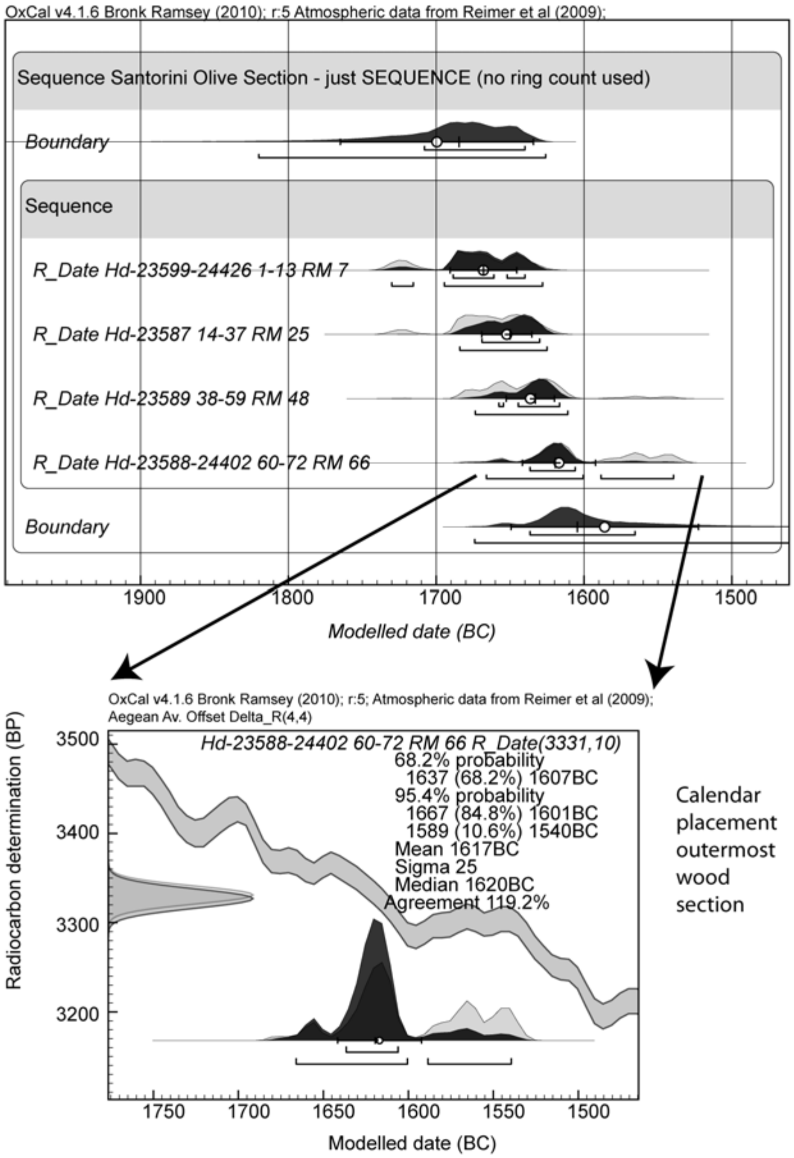

Figure 14 Calendar date placement of the Santorini olive branch sample reported by Friedrich et al. (2006) reconsidered using (i) just the growth sequence (older to younger, from center to outermost growth segment dated) and ignoring approximate ring counts reported by Friedrich et al. (2006) since there is some question over the ability to recognize (reliably and certainly regularly) tree-ring growth increments in olive by visual means (Wiener 2009:204–5); and (ii) a possible Aegean/Anatolian ΔR offset of 4 ± 4 yr (see text). Typical output from analysis of the model shown (Upper). No substantive change in the likely dating for the sample is evident versus the dates reported by Friedrich et al. (2006). Lower: The most likely 68.2% probability range for the center of the last dated segment is 1637–1607 BC, and the most likely 95.4% probability ranges are 1667–1610 BC (84.8%) and 1589–1540 BC (10.6%). The most likely date range is in the later 17th century BC. If a possible "largest likely seasonal offset" Aegean/Anatolian ΔR offset of 9 ± 4 yr (see text) is employed, then (typical output) the most likely 68.2% probability range for the center of the last dated segment is 1634–1604 BC, and the most likely 95.4% probability ranges are 1662–1653 BC (2.1%) and 1641–1538 BC (93.3%). Again, despite a slight increase in 16th century BC probability, the main most likely region (e.g. the most likely 68.2% region) is in the late 17th century BC. Data from OxCal using IntCal09 and a curve resolution of 5.

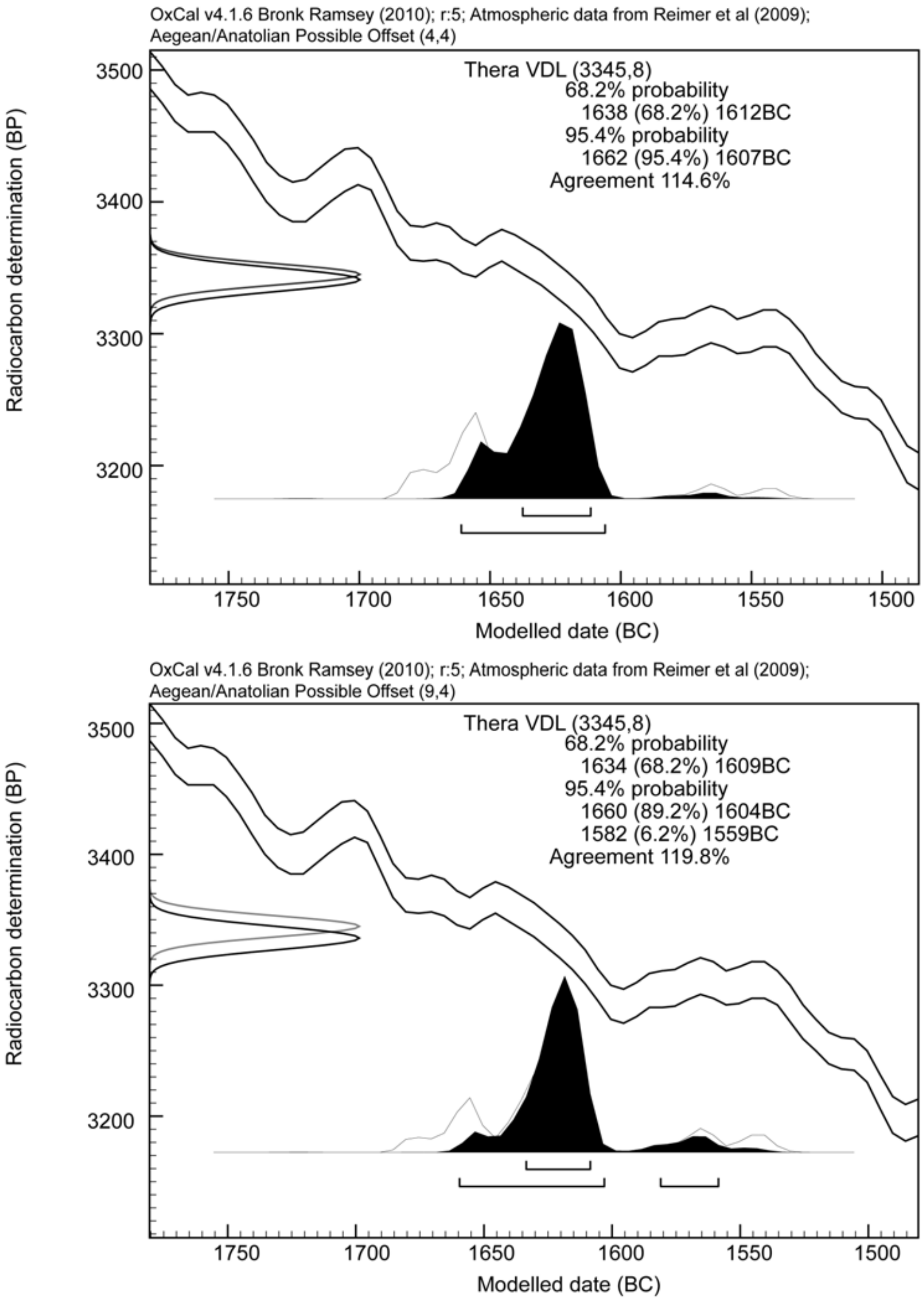

Figure 15 The calendar dating probability for the weighted average age of the ^{14}C determinations on short-lived plant material from the Santorini volcanic destruction level in terms of the Middle Minoan IIIB/Early Late Minoan IA to Late Minoan II data and sequence analysis published in the Manning et al. (2006) study (for data and model, see Manning et al. 2006 SOM), but reconsidered using: (i) Upper, a possible Aegean/Anatolian ΔR of 4 ± 4 for this period (see text), and (ii) Lower, a possible "largest likely seasonal offset" Aegean/Anatolian ΔR of 9 ± 4 for this period (see text). Data from OxCal employing IntCal09 and a curve resolution of 5.

Table 8 Comparison of the calendar date ranges calculated for 2 Aegean cases given a possible Aegean/Anatolian offset (ΔR) of 0, 4 ± 4, and ("largest likely seasonal offset") 9 ± 4 yr: see text. Typical output for analysis runs of OxCal models using IntCal09 with curve resolution set at 5. Case 1: the date of the mid-point of the outermost ^{14}C-dated segment of an olive branch from the Plinian pumice deposits on Santorini employing the ordered (oldest/inner wood to most recent/outermost wood—and no ring count estimates at all) ^{14}C information published by Friedrich et al. (2006) and considering a possible Aegean/Anatolian offset (ΔR) of 0, 4 ± 4, and ("largest likely seasonal offset") 9 ± 4 yr: see text. Model used listed in Appendix. Case 2: The date calculated for the Santorini volcanic destruction level (VDL) in the Model 1 analysis of Manning et al. (2006) considering a possible Aegean/Anatolian offset (ΔR) of 0, 4 ± 4, and ("largest likely seasonal offset") 9 ± 4 yr: see text. Model and data as in Manning et al. (2006) adding the line regarding the ΔR (e.g. `Delta_R("Aegean Av. Offset", 4, 4);`). We used this published model to examine the offset impact. We note that some additional Late Minoan IB data (for example) can now be added when exploring Aegean Late Bronze 1–2 chronology (see Manning 2009; Manning and Bronk Ramsey 2009).

	Santorini olive sample using just growth sequence/order (no ring count estimates). Modeled calendar age ranges BC for mid-point of last (outer) segment.		Santorini volcanic destruction level short-lived samples. Modeled calendar age ranges BC for the weighted average of these samples.	
Possible Aegean/ Anatolian offset (ΔR)	*68.2% prob.*	*95.4% prob.*	*68.2% prob.*	*95.4% prob.*
No ΔR	1637–1610	1677–1602 (92.3%) 1577–1559 (3.1%)	1641–1615	1660–1611
ΔR 4 ± 4	1637–1607	1667–1601 (84.8%) 1589–1540 (10.6)	1638–1612	1662–1607
ΔR 9 ± 4	1634–1604	1662–1653 (2.1%) 1641–1538 (93.3%)	1634–1609	1660–1604 (89.2%) 1582–1559 (6.2%)

from a conventional archaeological perspective). A key recent development in this regard is that an extensive study has found good compatibility between a ^{14}C-based chronology and the standard Egyptian historical chronology for the 2nd millennium BC (Bronk Ramsey et al. 2010). This indicates *a priori* that ^{14}C dating on good samples with appropriate analysis can offer precise and accurate dates in the east Mediterranean. In turn, it now seems likely that the Aegean-east Mediterranean-Egyptian archaeological linkages and associations in the 17th–16th centuries BC (especially) in supposed contradiction of the large bodies of sequenced ^{14}C data might have to be rethought: in particular, the archaeological dating of contexts/strata and/or objects and ^{14}C samples at the site of Tell el-Dab'a, which are held to disprove the Aegean ^{14}C evidence by some scholars (e.g. Bietak 2003; Bietak and Höflmayer 2007; Wiener 2009), now need critical re-examination—as already argued by Warburton (2009b; see also Manning and Kromer 2010).

14TH–13TH AND 9TH–8TH CENTURIES BC

Kromer et al. (2010) report new measurements on known-age German oak 1360–1320 BC that exhibit an offset (older ages by on average 27 ^{14}C yr). In view of the good agreement between the Heidelberg Laboratory and other the calibration data sets in other periods (e.g. 1650–1480 BC: Kromer et al. 2010), and noting also that there are in fact relatively few underlying data in the IntCal09/04 data set for this interval, it appears plausible that this offset is real and that the IntCal09/04 curve may require revision (we note the paper of Hogg et al. [2009], which also reports an offset from IntCal04/09 of up to 13.7 yr, and recommends additional analyses to strengthen IntCal04/09; and we concur with this assessment at least for this 14th–13th century BC interval). As noted by Kromer et al. (2010), the ^{14}C measurements on the Gordion Area dendrochronology across the same interval appear to yield a similar situation (and provide some additional measure of support for revising the existing IntCal09/04 curve in this period) (Figures 5 and 11). The Gordion Area data also provide some support for the reality of ^{14}C inversions around 1325 and 1225 BC. Visual inspection of Figures 5 and 11 might suggest the possibility of a smaller but possibly real offset operating around 1080–990 BC.

In the interval 850–750 BC, the ^{14}C record from the Gordion Area juniper trees continues to show, on average, a small offset (older ^{14}C ages) as previously observed (Kromer et al. 2001; Manning et al. 2001). With additional measurements of samples over this interval, the apparent offset is now smaller than initially reported but remains evident (Manning et al. 2005; Kromer et al. 2010) for Gordion tree rings 1665 to 1754.5 (or about 850.5 to 751 BC); the average offset, Gordion-IntCal09, is 28.8 ± 26.3 ^{14}C yr (or a ΔR in OxCal of typically about 15.4 ± 11.3 yr). We continue to regard the cause as linked with an emphasizing of small growing-season offsets (and timing of ^{14}C uptake into the tree rings) during the contemporary major solar minimum when ^{14}C production and flux was enhanced. Normally, such small differences in growth timings within the mid-latitudes of the Northern Hemisphere are below detection level.

CONCLUSIONS

We have completed a long-term project to investigate ^{14}C levels in the second to early 1st millennia BC in the east Mediterranean, and at the same time we have obtained a precise near-absolute calendar placement for the long floating Gordion Area juniper tree-ring chronology. The ^{14}C-dated time-series (and so the dendrochronology relative years 776 to 1754) is placed 1729 to 751 BC within about +3.3/–2.7 yr error limits at 68.2% confidence, and within conservative +6/–8 yr error limits at 95.4% confidence. ^{14}C measurements over many years have proved stable and replicable at the Heidelberg Radiocarbon Laboratory, both for Gordion Area juniper (this paper and results in Kuniholm et al. 1996; Kromer et al. 2001; Manning et al. 2001, 2003, 2005), and for German oak (Kromer et al. 2010). Measurements on German oak at Heidelberg compare well with measurements on equivalent samples at Seattle (Kromer et al. 2001: Figure 1) and the IntCal09/04 curve 1650–1480 BC (Kromer et al. 2010). We find good agreement with likely only a very small regional (growing season related) offset (ΔR ~0–4 yr) between our ^{14}C data from the Gordion Area juniper dendrochronology and the standard Northern Hemisphere ^{14}C records (German and Irish oak) 1730–1350 BC (Stuiver et al. 1998a; Reimer et al. 2004, 2009). We observe no evidence compatible with claims (Keenan 2002) of a purported depletion of ^{14}C levels in the Mediterranean region across this interval; the good match of a 7-decade ^{14}C record and wiggle-match from an oak sample from the coastal west Anatolian site of Miletus in the later 18th through earlier 17th centuries BC (Bronk Ramsey et al. 2004; Galimberti et al. 2004; Manning et al. 2006) provides additional evidence against such claims in this same time period (see Figure 11). In the later 14th–13th centuries BC, the Gordion Area data appear, like new measurements on known-age German oak (Kromer et al. 2010), to suggest some minor revision may be necessary to IntCal09/04, and to indicate also the reality of key age inversions such as around 1325 and 1225 BC. A regional (growing season related) minor offset in tropospheric ^{14}C levels in the interval 850–750 BC has become smaller with new data (compared to when first reported), but nonetheless remains observable and of interest. It is worth highlighting that in both these cases, the difference or small offset concerns the ^{14}C timescale, since the Gordion Area dendrochronological timescale is secure over the relevant tree rings = calendar years.

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APPENDIX

Example OxCal Run File for analyses shown in Figure 14 and listed in Table 8 Case 1. This is for offset ΔR 4 ± 4 yr.

```
Plot()
 {
  Delta_R("Aegean Av. Offset", 4, 4);
  Sequence( "Santorini Olive Section - just sequence inner to outer, no ring counts")
  {
   Boundary ();
   Sequence( )
   {
    R_Date( "Hd-23599-24426 1-13 RM 7", 3383, 11);
    R_Date( "Hd-23587 14-37 RM 25", 3372, 12);
    R_Date( "Hd-23589 38-59 RM 48", 3349, 12);
    R_Date( "Hd-23588-24402 60-72 RM 66", 3331, 10);
   };
   Boundary( );
  };
 };
```

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