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The Course of ^{14}C Dating Does Not Run Smooth: Tree-Rings, Radiocarbon, and Potential Impacts of a Calibration Curve Wiggle on Dating Mesopotamian Chronology

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Abstract

We review evidence for near-absolute calendar date estimates for the Waršama Palace at Kültepe and the Sarıkaya Palace at Acemhöyük (Turkey) in light of a forensic examination of the radiocarbon calibration curve. Both palaces can be linked indirectly (but closely) to the Assyrian Revised Eponym List (REL) and can thus be connected with the Mesopotamian historical chronology. The possible relevance of some apparent features of detail in the radiocarbon calibration dataset is noted. In particular, we explore a wiggle-match of the dendro-^{14}C sequences from the palaces employing the IntCal98 calibration curve, which better represents what we argue seems to be a pronounced "wiggle" in contemporary atmospheric ^{14}C ages around 1835 BCE. This "wiggle" is missing in the more smoothed IntCal13 curve (the current standard northern hemisphere radiocarbon calibration curve). Using IntCal98, we find a best fit 8 years later than previously suggested. We suggest that this issue of "detail" requires further investigation in order to achieve a precise solution for Mesopotamian chronology. If this wiggle is relevant, we find that the dendro-^{14}C-derived dates are more in agreement with the Low Middle Chronology, thus refining previous conclusions. This result is also discussed in the framework of the radiocarbon-backed high Middle Bronze Age chronology for the southern Levant and a recently published radiocarbon date for Illahun Papyrus 10012B, reporting the anticipated rise of Sothis, one of the key-anchors of Egyptian historical chronology.

Introduction

A recent paper (Manning et al. 2016) presented an integrated tree-ring and radiocarbon (^{14}C) analysis to provide high-resolution dates for the construction of the Waršama Palace at Kültepe and the Sarıkaya Palace at Acemhöyük in Turkey based on obtaining near-absolute calendar date estimates for the outermost tree-rings (bark or waney edge) of building timbers from both monuments.[1] The dating reported in the Manning et al. paper[2] employed the current mid-latitude northern hemisphere IntCal13 radiocarbon calibration curve.[3] When linking these dendro-^{14}C-derived construction dates with the textual records available from the two sites, and placing these construction dates in terms of the Assyrian Revised Eponym List (REL)[4]—which are reconstructed on the basis of the seven currently known eponym lists from Kültepe and the partially overlapping Mari Eponym Chronicle—we found that the only compatible linkage is with the Middle Chronology (MC) or the (just) 8-years-later Low Middle Chronology (LMC) for Mesopotamia. This finding has widespread relevance to Mesopotamian history and archaeology, ending a previous long-running uncertainty and debate over the correct timeframe,[5] but it is also pertinent to contexts and sequences that are related to Mesopotamian history. For example, the findings invalidate arguments constructed based on other Mesopotamian chronologies, such as the Low Chronology, including Bietak's use of the Low Chronology via Hazor, to date contexts at the eastern Mediterranean super-site of Tell el-Dabʿa in Egypt.[6] The Middle Chronology or Low Middle Chronology in contrast offers general support for an early, raised date for the end of the Middle Bronze Age in the Levant, as argued recently on the basis of radiocarbon analyses from several sites in the Levant,[7] and as indicated both by radiocarbon analyses at Tell el-Dabʿa itself[8] and wider reconsideration of the site's chronology and links and the most likely dating of the Hyksos king, Khayan.[9]

The level of chronological resolution available from the integrated dendro-^{14}C analysis in Manning et al. 2016 was stated as unable to resolve between the two very similar alternatives, just 8 calendar years apart, of the Middle Chronology or the Low Middle Chronology. In this paper we further investigate the currently available radiocarbon calibration evidence to see if any greater precision is potentially available and then offer a few clarifying observations and comments. We suggest that perhaps we can see a route to a more precise, final, resolution and propose a strategy that we will follow in future work to achieve this. Three minor sets of corrections to the Manning et al. 2016 paper are also noted in the Appendix (below).

Radiocarbon Calibration and the Anatolian MBA Tree-Ring-^{14}C Series in Detail

In the Manning et al. 2016 paper, the tree-ring sequenced set of ^{14}C data from the Anatolian Middle Bronze Age tree-ring chronology comprised of cross-dated timber samples from the sites of Acemhöyük, Karahöyük, and Kültepe were wiggle-matched against the IntCal13 ^{14}C modeled calibration curve (the current international standard then, and as we write this text). The IntCal13 curve was modeled at 1 calendar year resolution. The analyses reported thus employed the international standard at highest resolution. However, as shown in the Manning et al. 2016 Supporting Information file,[10] in figures O and P, the IntCal13 modeled curve is a smoothed record trying to best fit the large set of raw ^{14}C data forming the IntCal13 dataset for this period. The question thus arises: has the smoothing involved in creating the IntCal13 curve potentially removed relevant details that might affect the exact placement of the Anatolian MBA time-series? Currently, we only have the raw IntCal13 dataset to consider in this regard. We note this point because recent work has indicated that there are some very short-term (e.g., annual-scale) events that may have created specific "spikes" and so marker-features in the ^{14}C record—and hence in the radiocarbon calibration curve (e.g., Miyake et al. 2012; 2013; and for an example of work exploiting one of these very dramatic changes in ^{14}C levels to achieve precise annual dating, see Wacker et al. 2014).[11] However, in all but the most dramatic cases—e.g., the 775–774 CE and 993–994 CE cases identified by Miyake et al.[12]—these "spikes" will only be evident if the calibration record is more highly resolved than at present. Such "spikes" could be of key significance for (among other things) very precise, even exact, archaeological dating where they can be recognized and exploited.[13] The available ^{14}C data for the period relevant to the Anatolian MBA tree-ring time series, broadly 2100–1700 BCE, do not, however, suggest that such a major or dramatic ^{14}C event is present (contrast the cases and possible cases discussed in Dee and Pope).[14] But we suggest that there are perhaps smaller, but substantive, details that might nonetheless be important for this period, especially

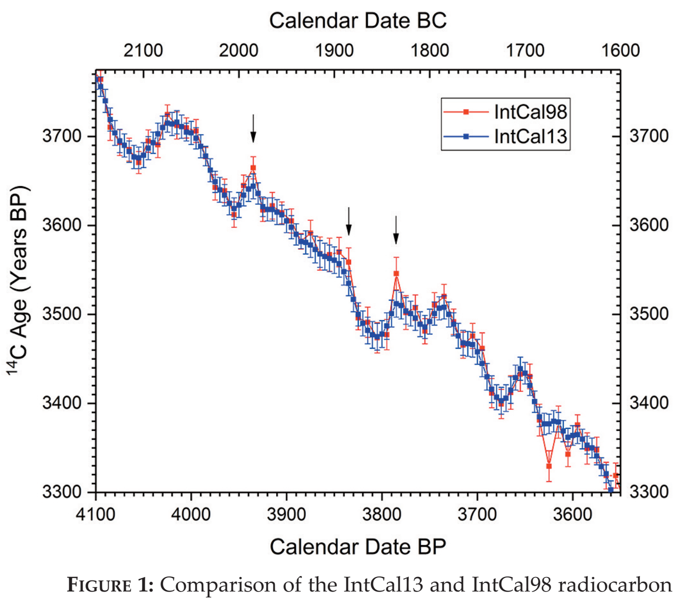

Figure 1: Comparison of the IntCal13 and IntCal98 radiocarbon calibration curves over the time period relevant to the calendar placement of the Anatolian MBA tree-ring series. The arrows indicate features discussed in the text. The plotted data points show the 1σ (SD) errors.

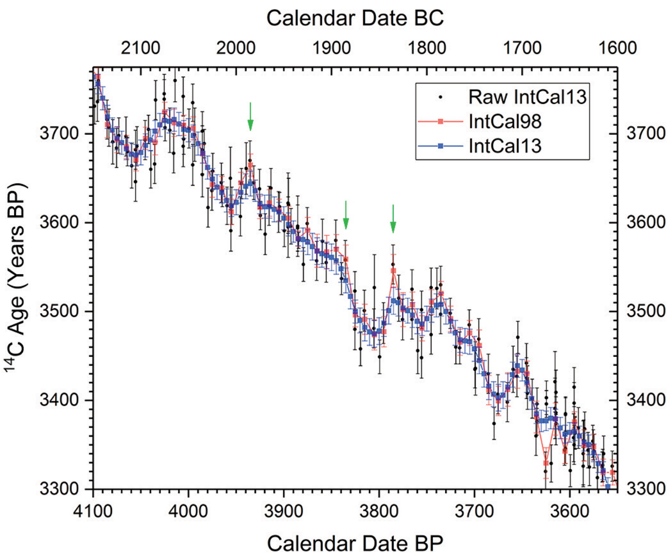

FIGURE 2: Comparison of IntCal13 versus IntCal98 as in Figure 1, but also now showing the raw data from the IntCal13 dataset. The same three features are indicated by the arrows as in Figure 1. All plotted data points shown with 1σ errors.

if greater calibration curve resolution can be achieved.

As one indication of the possibility (or not) of chronological movement, and the scale of the possible differences, that approaches to modeling of the raw ^{14}C calibration data could make, we can compare two existing radiocarbon calibration curves: IntCal13[15] and the earlier and less smoothed IntCal98 dataset,[16] which, for the relevant period, used mainly the same underlying data. Figure 1 compares the IntCal13 versus IntCal98 calibration curves in the period of interest for the Anatolian MBA wiggle-match. It is obvious that IntCal98 is less smoothed and the arrows indicate in particular 3 loci where there are relatively substantive differences with larger apparent changes in ^{14}C age trend at these times indicated in the IntCal98 versus IntCal13 record. Figure 2 shows the same information as Figure 1, but adding in the raw data from which IntCal13 was modeled (for the raw IntCal13 data, see the CHRONO IntCal13 Database: http://intcal.qub.ac.uk/intcal13/).We can see how the IntCal98 record tended to follow some variations in the underlying data more closely—including around the three loci noted by the arrows (same as in Figure 1)—whereas IntCal13 is more smoothed.

Does use of one or the other of these two slightly different calibration curves affect the calendar placement for the Anatolian MBA time-series? The answer in our case is yes: there is a small but potentially important difference. Figure 3 shows and compares the wiggle-match of the data against the two curves: at the top (A) versus the IntCal13 calibration curve (as reported in the Manning et al. 2016, table 2 paper as Model 7a), versus at the bottom (B) the IntCal98 calibration curve (both with calendar resolution modeled at 1 year and default OxCal settings). This modeling employs all the MBA tree-ring time series ^{14}C data, except OxA-30907 which exhibited an anomalous $\delta^{13}C$ measurement in the accelerator versus the mass spectrometer value, and so is regarded as suspect and is thus excluded. The best fit against IntCal98 is slightly later, the mean best fit is 9 years later (1812 BCE versus 1821 BCE*), but most notably, by eye, it is apparent that the data seem overall to better fit against the IntCal98 curve. In particular, in the period around 1835 BCE, the data in B are generally somewhere around the IntCal98 curve versus lying in free space (as in A). The fit around 1885 BCE and 1985 BCE (the other two areas along with 1835 BCE indicated by the arrows in Figures 1–2) also looks slightly better against IntCal98—especially for the date at RY514.5 (a high-precision measurement from Heidelberg, Hd-22955), indicated by the arrow in Figure 3B. Application of the RScaled outlier model[17] as employed in Manning et al. 2016 finds 6 outliers against IntCal13 (Figure 3A, cyan-colored data points) versus only 4 outliers against IntCal98 (Figure 3B, cyan-colored data points). If the IntCal98 run (Figure 3B) is re-run in OxCal excluding the four outliers, the best fit only changes to 1 year later (Figure 4). This best fit in Figure 4 is 8 calendar years later than the best fit excluding outliers for the data set against IntCal13 (Model 8a in Manning et al. 2016) as reported in Manning et al. 2016, table 2, and it is 9 years later than the best fit minus outliers for (the very slightly different) Model 8b against IntCal13 reported in Manning et al. 2016. (Model 8b combined the Oxford and Vienna laboratory data on the identical tree-rings, whereas Model 8a treated

* We note that repeated runs of the time-series can lead to a 0–1 year variation in reported results. Thus the mean ± SD for the whole series (except OxA-30907) is typically returned as 1812±2 BCE (IntCal98) and 1821±8 BCE (IntCal13), but sometimes the runs report 1811±2 BCE and 1822 ± 8 BCE. Thus an additional 0–1 year error should be regarded as applying to the numbers quoted. This is clearly negligible.

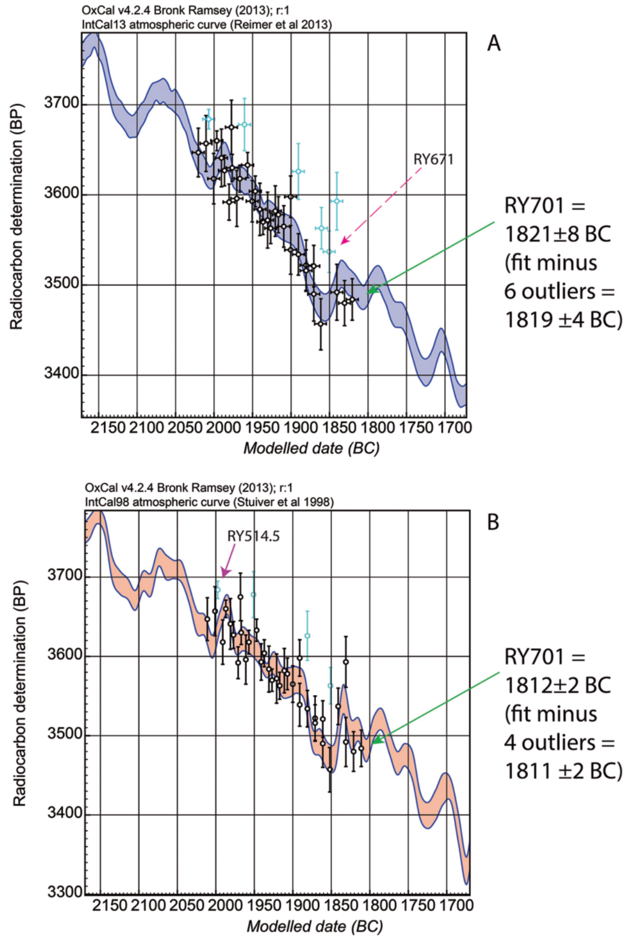

Figure 3: Tree-ring series ^{14}C wiggle-match (Christopher Bronk Ramsey, Johannes van der Plicht, and Bernhard Weninger, "'Wiggle Matching' Radiocarbon Dates," *Radiocarbon* 43 [2001]: 381–389) of the Anatolian MBA dataset (excluding only OxA-30907 as explained in the text) versus: top (A), the Intcal13 calibration curve (this is the fit reported in Manning et al. 2016, table 1 as dating model 7a); and bottom (B), the IntCal98 calibration curve. OxCal 4.2 (Christopher Bronk Ramsey, "Bayesian Analysis of Radiocarbon Dates," *Radiocarbon* 51 [2009a]: 337–360) employed with resolution set at 1 year. Both calibration curves are shown as 1σ bands; the data points in each plot represent the μ±σ (μ = mean) calendar best fit for each element on the x axis and the 1σ ^{14}C age range for each element on the y axis. The data points in each plot colored cyan (6 in A and 4 in B) are outliers applying the RScaled outlier model (Christopher Bronk Ramsey, "Dealing with Outliers and Offsets in Radiocarbon Dating," *Radiocarbon* 51 [2009b]: 1023–1045) as in Manning et al. 2016. The mid-point of the last (latest) sample placed is Relative Year (RY) 701 in terms of the Anatolian MBA tree-ring series (indicated by the arrows). RY671 is also indicated in A and RY514.5 is also indicated in B (see text).

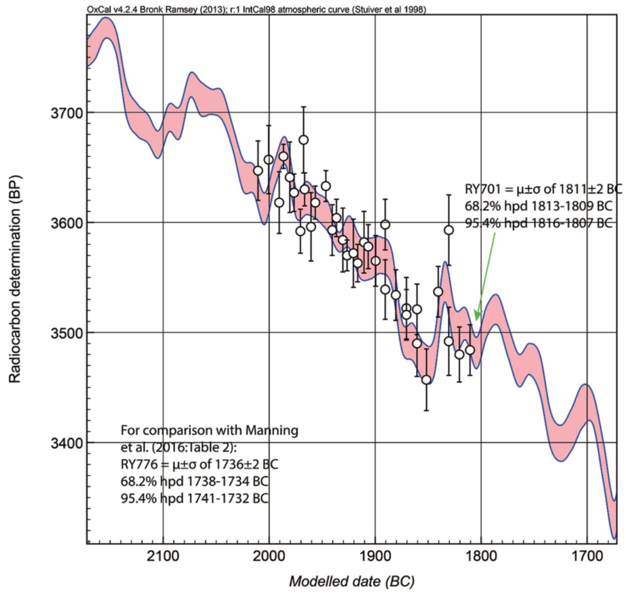

Figure 4: The best tree-ring ^{14}C wiggle-match (Bronk Ramsey et al. 2001) of the Anatolian MBA dataset minus outliers (see Figure 3B) versus the IntCal98 calibration curve. OxCal 4.2 (Bronk Ramsey 2009a) employed with resolution set at 1 year. Placement is -1 year versus Figure 3B. The IntCal98 calibration curve is shown as a 1σ band; the data points represent the μ±σ calendar best fit for each element on the x axis and the 1σ ^{14}C age range for each element on the y axis. For the key calendar date ranges from this wiggle-match for dating the Primary Construction and likely Earliest Use of the Waršama Palace at Kültepe and the Sarıkaya Palace at Acemhöyük, see text and Table 1.

them separately; Model 7b in Manning et al. 2016, table 2 if re-run employing IntCal98 offers a best fit for RY776 at 1736±2 BCE, mean ±SD, 10 years later than the fit against IntCal13 as reported in Manning et al. 2016, table 2; note the typo correction in the Appendix, below.) We employ the Figure 4 fit given in this paper from here on; this is 8 years later than the fit employed as the preferred fit (Model 8a) in Manning et al. 2016.

Are there any considerations that might help us decide which wiggle-match fit is better? We suggest that a key issue concerns which data comprise the extra "outliers" against the different curves. The four outliers against IntCal98 are also outliers versus IntCal13: the extra two outliers versus IntCal13 are the two accommodated against IntCal98 by the sharp upwards wiggle in the IntCal98 curve at ca. 1835 BCE. So: is this upwards wiggle real? The

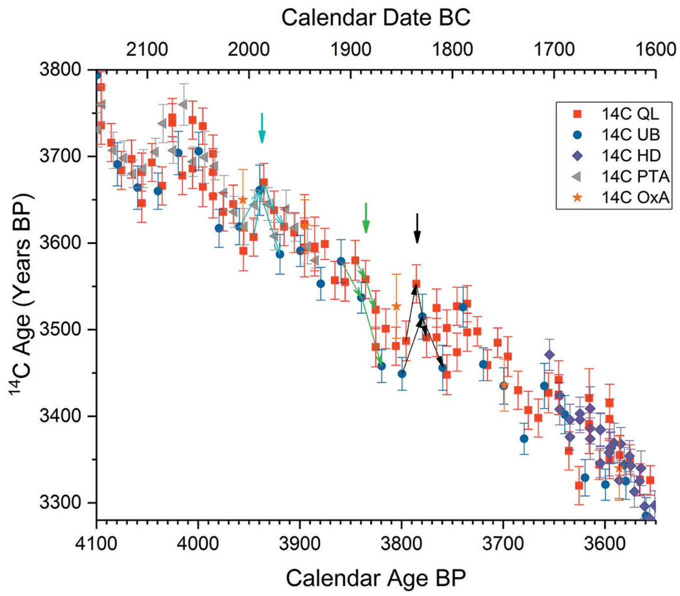

Figure 5: The raw IntCal13 calibration dataset for the period 4100–3550 cal BP. Data points shown with 1σ errors. QL = University of Washington dataset, UB = Queen's University of Belfast dataset, HD = Heidelberg, PTA = Pretoria and OxA = Oxford (Bronk Ramsey) (see the CHRONO IntCal13 Database: http://intcal.qub.ac.uk/intcal13/ for the datasets). The vertical arrows mark the same periods indicated in Figures 1–2. The arrows linking some of the data points indicate (black) the distinct 1835 BCE wiggle represented in *both* the QL and UB datasets, (green) the steep change in ^{14}C values ca. 1910–1870 BCE in *both* the QL and UB datasets, and (cyan) the wiggle centered 1990/1985 BCE in *both* the QL and UB datasets: see text.

raw IntCal13 dataset for the period is shown in Figure 5 with the source laboratory for each data-point indicated. The wiggle around 1835/1830 BCE is, notably, represented in *both* the QL (University of Washington) and UB (Queen's University Belfast) datasets. Thus it was recorded by two different radiocarbon laboratories independently using different known age tree-ring samples. The scale of this wiggle is also of the same scale in both datasets (a jump upwards in mid-point values of 66 ^{14}C years to ca. 1835 BCE or ca. 1830 BCE): just the UB data values are both lower, and the QL values both higher. Hence there is good reason to assume that this *is* a real feature in the atmospheric radiocarbon record for the mid-latitudes of the northern hemisphere. We may further note that the other two features identified as distinguishing IntCal98 versus IntCal13 in the time period of interest (see loci marked with arrows in Figures 1 and 2) are also evident in both the QL and UB datasets (Figure 5, see green and cyan arrows), indicating that IntCal98 is better reflecting instances of apparently real relatively marked variation in ^{14}C levels over short periods (one to a few decades) than IntCal13. Of the two additional data points found to be outliers against IntCal13 (Figure 3A), one, at RY671 (indicated in Figure 3A) is notable, as it comprises the weighted average of two independent, but very

Table 1: Calendar date BCE estimates for the primary construction (PC) timbers with bark or waney edge (giving the exact cutting date), and likely earliest building use (EU) dates, for the Waršama Palace at Kültepe and the Sarıkaya Palace at Acemhöyük from Figure 4. This table revises Manning et al. 2016, table 3 *if* we instead employ the IntCal98 radiocarbon calibration curve, and, in particular, *if* the "wiggle" ca. 1835 BCE that is more strongly represented in the IntCal98 calibration dataset is a real feature (so a hypothesis pending confirmation or negation).

MBA Chronology Relative Years (RY)	Primary Construction (PC), *Likely Earliest Use (EU)*	μ±σ	median	68.2% hpd (highest posterior density)	95.4% hpd (highest posterior density)
		Calendar Dates BCE			
RY670	Waršama PC	1842±2	1842	1844–1840	1847–1838
RY671	Waršama PC	1841±2	1841	1843–1839	1846–1837
RY672	Waršama PC	1840±2	1840	1842–1838	1845–1836
RY673	***Waršama EU***	***1839±2***	***1839***	***1841–1837***	***1844–1835***
RY730	Sarıkaya PC	1782±2	1782	1784–1780	1787–1778
RY731	Sarıkaya PC	1781±2	1781	1783–1779	1786–1777
RY732	***Sarıkaya EU***	***1780±2***	***1780***	***1782–1778***	***1785–1776***

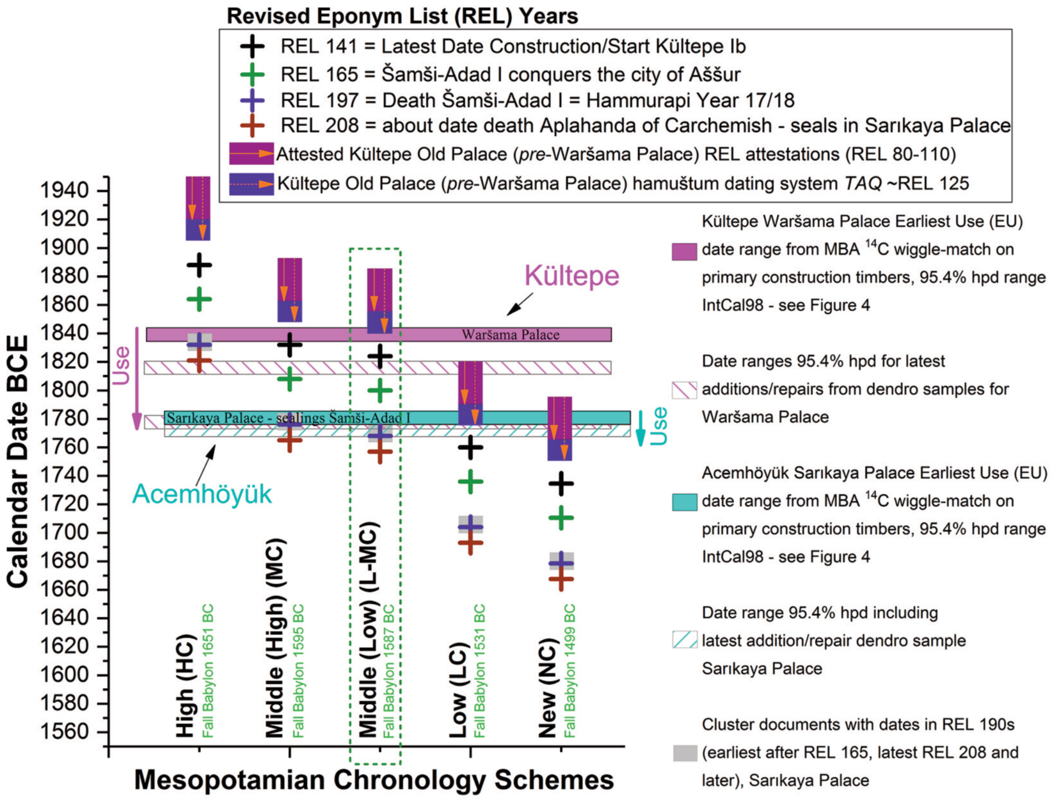

FIGURE 6: Manning et al. 2016, fig. 9 (*corrected*; see text and Figure 7, below) replotted with the tree-ring samples placed according to the best fit against the IntCal98 radiocarbon calibration curve (from Figure 4 above; model run excluding outliers). The IntCal98 95.4% hpd (highest posterior density) calendar ranges for the tree-ring ages are (mid-point) 7.5 calendar years later (lower) than the mid-point of the ranges from IntCal13 and shorter (better defined), thus the 95.4% probability range is ± 4.5 years versus IntCal98 compared to ± 8 years versus IntCal13 (as in Figure 7).

similar, ^{14}C measurements for this sample: OxA-30896 of 3547±33 BP and OxA-31520 of 3528±31 BP. Thus again this is no single-case "blip" or anomaly, but a replicated result. Since it appears to conform to the replicated evidence in the calibration dataset for a jump in ^{14}C ages around this time, it seems likely consonant real evidence. The better fit of this observed evidence versus the recorded jump in contemporary ^{14}C values possible through use of the IntCal98 calibration curve thus seems to give a likely better real calendar placement than the fit versus the more smoothed IntCal13 dataset in this case. This issue deserves further clarification and potentially offers a route to a near-definitive resolution of this chronological placement.

Where does this leave us given the data available at present? It would seem that perhaps the fit of the Anatolian MBA tree-ring time series about 8 years later against IntCal98 might be the "best" available placement: see Figure 4. What does this small shift indicate for the historical chronology discussion? It would place the likely earliest use (EU dates in Manning et al. 2016, table 3; that is, the year following the latest of the cutting or bark dates for the timbers from each structure) for the Waršama Palace (RY673) at Kültepe at 1839±2 BCE (mean ±SD) and for the Sarıkaya Palace (RY732) at Acemhöyük at 1781±2 BCE (mean ±SD). If we revise the analysis in Manning et al. 2016, the dates for the primary construction (PC) (date of outermost ring of samples with bark) and likely earliest use (EU) at the Waršama Palace and Sarıkaya Palace are as in Table 1 (revising Manning et al. 2016, table 3). If we then compare the 95.4% probability ranges available for the construction/earliest use and further additions/repairs to each building available from the fit of the Anatolian MBA chronology in Figure 4 versus the REL dates associated with documents from the sites or key persons as placed according to the various Mesopotamian chronologies (please note

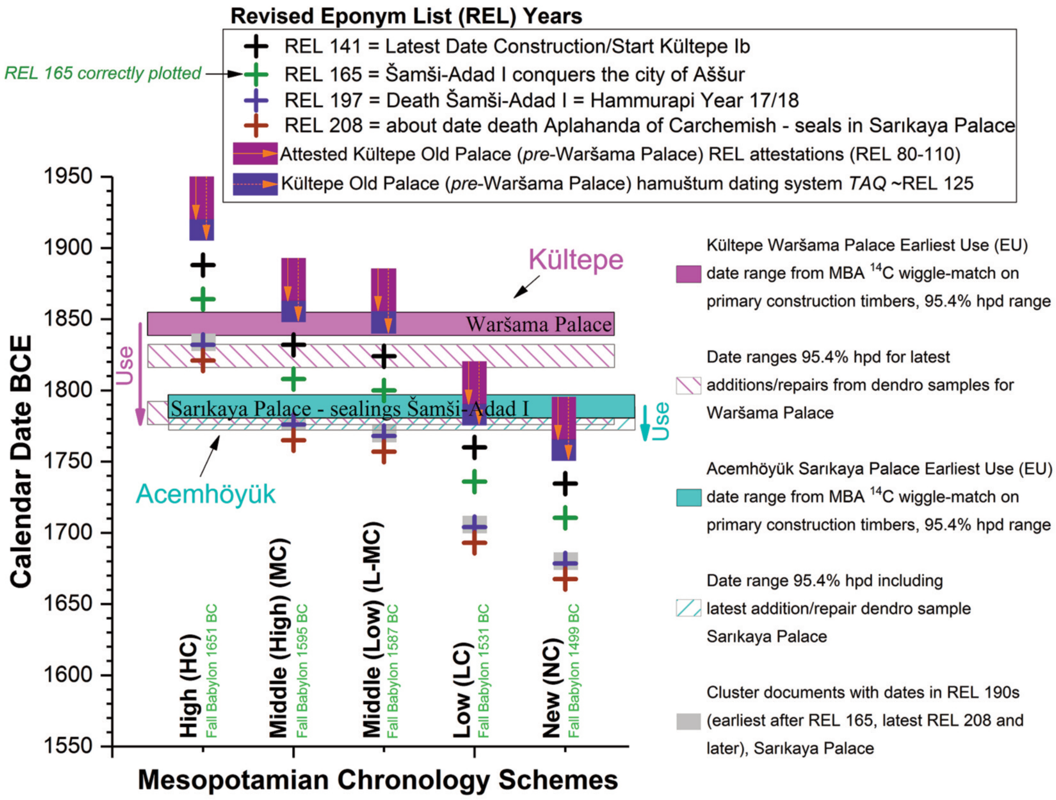

FIGURE 7: Manning et al. 2016, fig. 9 *corrected* to display the green cross symbol indicating REL 165 in the correct location (by mistake the original published Figure 9 plotted the green cross at REL 191; note REL 165 was correctly plotted in Manning et al. 2016, fig. 8).

the correction to Manning et al. 2016, fig. 9 discussed in the Appendix below), we get the revised scenario shown in Figure 6. While hardly decisive, this revision and the 8 years later placement and the narrower dating range available from the apparently better fit versus IntCal98 (and in particular the ca. 1835 BCE "wiggle"), all combine to offer a fit that is overall slightly more compatible with the Low Middle Chronology (LMC). In particular, it seems slightly better to allow for the later couple of decades of Šamši-Adad I's rule to lie in the initial period of use of the Sarıkaya Palace and for the cluster of sealed bullae likely dated in the REL 190s[18] to lie after the building was constructed and in its earlier years (whereas the Middle Chronology, 8 years earlier, has to "squash" all the evidence into literally the very first few years of the building's possible lifetime). The difference in assessment available when employing the IntCal98 fit versus the IntCal13 fit can be observed by comparing Figure 6 with Figure 7, which shows the Manning et al. 2016, fig. 9 scenario from IntCal13 (but correcting the plotting of REL 165: see Appendix). With IntCal13 there is less of the "squashing" problem for the Middle Chronology and the dendro-^{14}C wiggle-matched dates are less narrowly defined (16 years range at 95.4% probability with IntCal13 versus 9 years range at 95.4% probability with IntCal98) which again allows more apparent "negotiation" space. Therefore, if it is correct to rely on the wiggle around 1835 BCE as argued above, we achieve greater resolution and a stronger case to resolve in favor of the Low Middle Chronology.

FUTURE CHRONOLOGICAL RESOLUTION?

The brief investigation in this paper of the issue of the radiocarbon calibration curve details, their impacts regarding the exact placement of the Anatolian MBA tree-ring series, and the possibility of a significant real "wiggle" ca. 1835 BCE that is downplayed (overly smoothed away) in the IntCal13 radiocarbon calibration curve, leads to the obvious next step and a project to: (i) confirm or deny the existence of a real and sharply defined "wiggle" in the northern hemisphere atmospheric radiocarbon record around about 1835 BCE; (ii) clarify and resolve exactly when in calendar time this wiggle occurred, since the current underlying radiocarbon calibration data in this period are based on samples mainly of 10 or 20 year blocks of known-age wood, and we need rather greater resolution (e.g., annual or near annual); and (iii) add some additional resolution to the radiocarbon data in this period from the Anatolian MBA tree-ring series so as to determine if we can wiggle-match our dendrochronological data with such a better resolved known-age calibration record in order to achieve a best and almost exact resolution of Mesopotamian chronology. With the collaboration of colleagues, the present writers are now engaged on this project and will report in due course. It should be stressed that the present paper presents a hypothesis: it seems that perhaps there is a detail in the radiocarbon record that is not sufficiently represented in the current standard northern hemisphere record. This might be significant and allow a very slightly different (chronologically lower) and even more closely resolved date of the Anatolian MBA tree-ring series than reported in Manning et al. 2016. At present we lack the data to know this, but future work will determine the correct answer and has the promise of an almost exact solution for Mesopotamian chronology.

Discussion and Conclusions

A detailed consideration of the radiocarbon calibration curve, and the likely reality of the key "wiggle" in the northern hemisphere atmospheric radiocarbon record around 1835 BCE, *suggests* that we may in fact be able to resolve between the Middle and Low Middle Chronologies for Mesopotamia in favor of the Low Middle Chronology—and we will pursue further work to test and resolve this hypothesis. This finding is in accord with the recent reassessments of the astronomical and textual data, which have also indicated that the Low Middle Chronology is most likely and compatible with all the available data.[19] In a forthcoming article, Klaas Veenhof discusses the nature of the assemblage at Acemhöyük in view of the results presented in Manning et al. 2016.[20] The presence in the Sarıkaya Palace of two seal impressions made by the official Līter-šarrūssu before his cylinder was re-carved by a new owner at Tell Leilan pulls the material found at Sarıkaya backwards in time. Veenhof states that "since the tablet from Tell Leilan with the new name dates from the eponymy year 1783 BC, the original seal must have been impressed on the Acemhöyük bullae earlier." He thus associates the tablet from Tell Leilan with the Assyrian eponym Ikūn-pīya in REL 190. However, the majority of tablets from Tell Leilan are dated REL 198-202 and the text could therefore also be assigned to the Assyrian eponym Ikūn-pī-Ištar (Ikkupīya) in REL 202 = MC 1771 BCE instead. More chronological constraint is provided by the five bullae from the Sarıkaya Palace bearing the seal of Nagiha[n/tum] "daughter of Yahdun-Lim, king of Mari and the Sim'alites." As shown by Veenhof, her sealings probably document activities in the period before MC 1790–1785 BCE, which according to our modified scheme (the Low Middle Chronology = LMC) corresponds to the years 1782–1777 BCE. This fits with an earliest use of Sarıkaya in calendar years 1785–1776 BCE (the EU date for RY732) and leaves about half a decade for the deposit of the sealings of Nagiha[n/tum] during the first years of use of the palace.

Another effect of following the IntCal98 hypothesis for this topic in terms of historical reconstruction is the fact that it brings the destruction of the lower town at Kültepe and the construction of the Waršama Palace on the citadel mound into closer chronological proximity. With the revision of the dendrochronological results reported in Manning et al. 2016, the chronology that tied the textual data coming from the lower town to the datable wood samples from the citadels discussed in Barjamovic et al. 2012 was effectively severed. Lowering the absolute (calendar) chronology by 8 years (as in Figures 3B and 4) draws the relative and absolute chronologies of texts and timber at Kültepe closer together. The construction date of the Waršama Palace (latest primary construction = bark date of RY672 and hypothesized EU date of RY673) at calendar dates of RY672 = 1845–1836 BCE and RY673 = 1844–1835 BCE (following the wiggle-match in Figure 4) would correspond to REL 121–130 based on an 1838 BCE solar eclipse (see below). This would still not coincide with the transition between the lower town Level II, the last eponym attested in texts of Level II being REL 138 and the earliest eponym attested in texts of Level Ib being REL 142. However, the date of construction would not coincide with the apparent downturn in trade after REL 110 as proposed by Veenhof,[21] either, and one would have to revert to other commercial reasons for explaining the recession.[22] A slightly lowered Middle

Chronology is compatible with an independent analysis of astronomical data.[23] This identifies the 1838 BCE solar eclipse as the one associated with the birth of Šamši-Adad I and presents an intercalation pattern of the Old Assyrian calendar[24] as an additional independent argument in favor of the Low Middle Chronology.

A decision in favor of the Low Middle Chronology also allows for the possibility of an association of the poor visibility conditions inferred from the Venus tablet data during years 12–13 of Ammisaduqa (1627–1626 BCE) with a major volcanic eruption and aerosol/dust-veil episode, and of this, in turn, with the notable tree-ring growth anomaly observed from several locations in the northern hemisphere 1628–1626 BCE that has often been associated with the climatic impacts of a major volcanic eruption.[25] The enormous eruption of the Thera/Santorini volcano in the southern Aegean is the best known, and plausible,[26] low-to-mid-latitude northern hemisphere candidate. Such a date for the Thera/Santorini eruption, and the Low Middle Chronology synthesis for Mesopotamia, are both compatible with, and would support, the timeframe available from an inter-connected web of radiocarbon-dated archaeological and historical contexts from across the Aegean-eastern Mediterranean region, as well as recent re-thinking of the historical-archaeological evidence for chronology in Egypt in the Hyksos period.[27]

The possible relevance of the ca. 1835–1830 BCE "wiggle" discussed above even reaches directly to the chronology of Egypt. This "wiggle" affects the probabilities for the dating of what was reported recently as the "earliest astro-chronological datum" by Marcus et al.[28] Marcus et al. reported radiocarbon dates on Illahun Papyrus 10012B, which records the anticipated rising of the star Sothis (Sirius), and compared this with three of the proposed astro-historical solutions (combining the information about Sothis/Sirius with associated lunar observations): 1872 BCE, 1866 BCE and 1831–1830 BCE. If the "wiggle" in the radiocarbon record around 1835–1830 BCE is accentuated (thus real and substantive), and depending on its better and exact definition in calendar placement and ¹⁴C scale, then this could—especially if the approximate seasonal effect recognized for plant material growing in Egypt around the Nile River is included[29]—likely reduce the dating probabilities as reported in Marcus et al. 2016 employing IntCal13 for Papyrus 10012B around 1831–1830 BCE (see Figure 8) and so would render the "low" chronology solution for the Illahun astronomical information specifically around 1831–1830 BCE less likely to be correct. Such a scenario would, along with other available radiocarbon and historical evidence, favor one of the higher dating

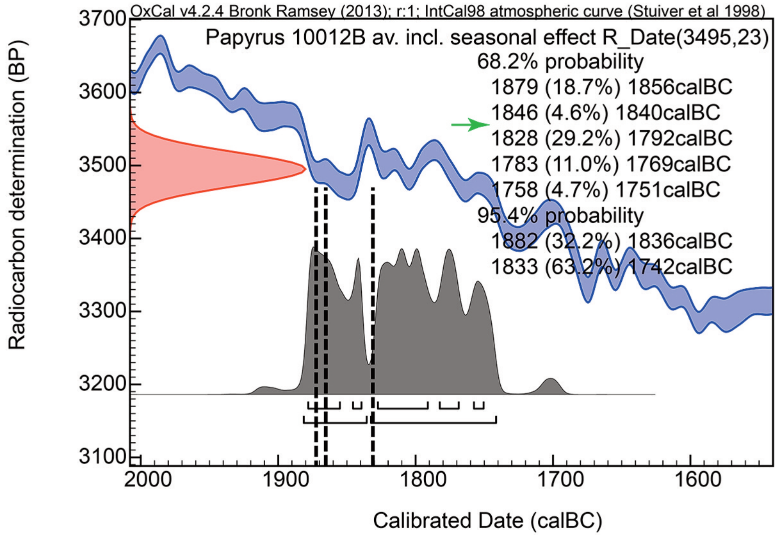

Figure 8: A revised version of the results shown in Figure 1 in Ezra S. Marcus, Michael W. Dee, Christopher Bronk Ramsey, Thomas F. G. Higham, and Andrew J. Shortland, "Radiocarbon Verification of the Earliest Astro-chronological Datum," *Radiocarbon* 58 (2016): 735–739 (which used IntCal13) but this time using IntCal98 in order to get greater accentuation of the apparent and potentially important "wiggle" ca. 1835–1830 BCE. Data from OxCal 4.2 with curve resolution set at 1 year (Bronk Ramsey 2009a). The weighted average value for the two dates on Illahun Papyrus 10012B including the approximate seasonal effect for Egypt as stated in Marcus et al. 2016, table 1 is employed (3495 ± 23 ¹⁴C years BP). The vertical dashed lines indicate the proposed astro-historical solutions of 1872 BCE, 1866BCE, and 1831–1830 BCE (Marcus et al. 2016, 736 with references). Whereas in Marcus et al. 2016, fig. 1 all three proposed solutions have similar probabilities, we see using IntCal98, and allowing for the ca. 1835 BCE wiggle, and allowing for the observed approximate ¹⁴C offset for samples growing in pre-modern Egypt (Michael W. Dee, Fiona Brock, Stephen A. Harris, Christopher Bronk Ramsey, Andrew J. Shortland, Thomas F. G. Higham, and Joanne M. Rowland, "Investigating the Likelihood of a Reservoir Offset in the Radiocarbon Record for Ancient Egypt," *Journal of Archaeological Science* 37 [2010]: 687–693), that now the 1831–1830 BCE solution has much less probability (none within the most likely 68.2% range, for example; the green arrow points to where there is no probability for the 1831–1830 BCE solution among the most probable 68.2% ranges).

solutions for the Middle Kingdom, e.g., 1872 BCE or 1866 BCE.[30]

We thus observe that the question of the reality and significance of this putative "wiggle" in the northern hemisphere radiocarbon record around 1835–1830 BCE assumes considerable importance for Near Eastern and East Mediterranean archaeology and history in the earlier second millennium BCE.

Appendix: Three Corrections to Note to the Manning et al. 2016 paper

1. Manning et al. 2016, fig. 9. By mistake the green crosses stated to indicate REL 165 in this figure, as published, in fact do not indicate REL 165; instead they mark REL 191. (In contrast: REL 165 is correctly shown in Manning et al. 2016, fig. 8). Figure 7 in the present paper presents a corrected version of Manning et al. 2016, fig. 9. The revised figure is identical with the published Manning et al. 2016, fig. 9 except that the green crosses now correctly indicate REL 165.

2. There is a typo in Manning et al. 2016, table 2 for Model 7b and the entry in the column giving the 95.4% hpd ranges. The text as published reads: 1773–1764 (9.8%), 1757–1773 (85.6%). The second occurrence of 1773 is an error; it should read 1733. Thus the correct ranges should read: "1773–1764 (9.8%), 1757–1733 (85.6%)." We thank Michael Roaf for bringing this to our attention.

3. S1 file typos. (a) There is a typo which occurs on both p. 30 and p. 33 of the published S1 file for Manning et al. 2016. The line of text in each case that reads:

```
R_Combine ("RY 677-685 = 701")
```

should in fact read:

```
R_Combine ("RY 697-705 = 701")
```

This was a purely typographic error in the label for the relevant R_Combine group and the correction does not affect the results; the correct RY intervals (697–705 = 701) were employed and labeled for the R_Date information in the R_Combine group. The section of code, corrected, should read at both p. 30 and p. 33 of the S1 file:

```
R_Combine ("RY 697-705 = 701")
     {
R_Date ("OxA-30899 RY 697-705 = 701", 3498,32);
R_Date ("OxA-31523 RY 697-705 = 701", 3470,31);
Outlier ("RScaled",0.05);
};
```

(b) A small error also occurs on p. 30 and p. 32 of the published S1 file for Manning et al. 2016. The line of text for OxA 29963 should in both cases read

```
R_Date ("OxA-29963 RY 656-672 = 660.5", 3457,28)
```

On p. 30 the incorrect last RY is given (662, whereas it should be 672). And an incorrect mid-point is stated at both p. 30 and p. 32 (clearly caused by the last typo). This sample was unusual in addition. We have re-checked the sample and records (and we thank Dr. Carol Griggs for her assistance). 50% of the wood in the 17 rings is represented by the middle of RY660 (the outer 10 rings are extremely narrow). Thus, on re-examination, the appropriate mid-point for the ^{14}C represented in the sample should, we believe, be regarded as RY660.5 (and not RY659 as stated in the S1 file). This is a tiny change and in fact makes (on repeated re-runs of the files against both IntCal13 and IntCal98) only either a 0 or 1 year difference in the placement of the time-series (see the note [asterisk] on page 72 of the present article).

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20 Veenhof in press.

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