floating Bronze-Iron Age Aegean dendrochronology (*31*) now must be shifted to ages ~22 years older—a matter of no little importance for archaeologists (*9*). Finally, it is clear that high-precision ^{14}C analyses provide a valuable tool for studying decadal- to century-scale atmospheric dynamics in the past.

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12. Samples (19 to 25 g) were pretreated with the AAA sequence (*32, 33*). All samples were combusted to CO_2, and their ^{14}C activity was determined by CO_2 gas counting for a total counting time of 7 to 10 days. The error as reported consists of Poisson counting statistics (~1.1 ‰) and regression analyses of background versus barometric pressure and standard versus gas purity (*34*). We consider our approach to the error calculation to be conservative, as the regression analysis includes empirical evidence of otherwise unspecified fluctuations in counter-performance in addition to the purely Poisson error components. The total error (1σ) of the ^{14}C age determination of a decadal wood sample was between 10 and 19 years for full-sized samples. For some replicates, we had less wood available (8 g), increasing the error to up to 29 years for these samples.
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Anatolian Tree Rings and a New Chronology for the East Mediterranean Bronze-Iron Ages

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We report an extensive program of high-precision radiocarbon dating to establish the best date for a floating 1599-year Anatolian tree ring chronology that spans the later third millennium B.C. through the earlier first millennium B.C. This chronology is directly associated with a number of key sites and ancient personages. A previously suggested dating is withdrawn and is replaced by a robust new date fix 22 (+4 or −7) years earlier. These new radiocarbon wiggle-matched dates offer a unique independent resource for establishing the precise chronology of the ancient Near East and Aegean and help resolve, among others, a long-standing debate in favor of the so-called Middle Mesopotamian chronology.

Over a period of 30 years, the Aegean Dendrochronology Project has built a robust, long, but floating tree ring chronology with the use of timbers collected from major archaeological monuments in Anatolia dating from the later third millennium B.C. through the earlier first millennium B.C. This chronology is central to the dating of some 22 Bronze and Iron Age sites (*1*) and forms a pivotal reference point for the archaeology and history of the eastern Mediterranean. The core of the chronology consists of 1026 years of cross-dated and well-replicated tree rings preserved at the Phrygian capital city of Gordion, particularly from the Midas Mound Tumulus grave chamber, the world's oldest standing wooden building (*2, 3*). We report

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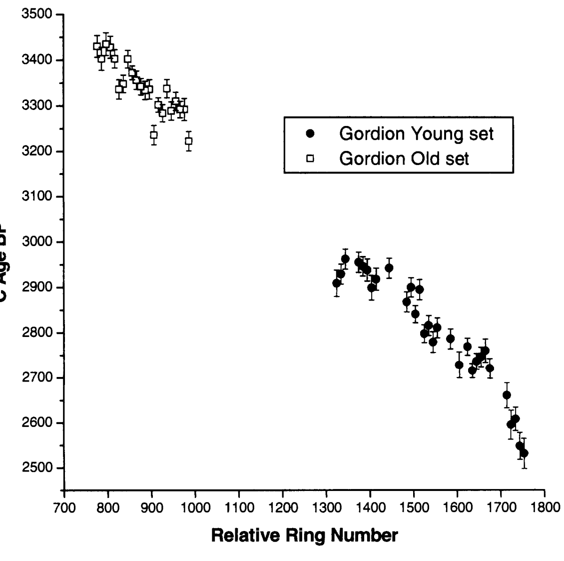

Fig. 1. Radiocarbon data with 1σ errors from decadal tree ring samples from wood series recovered from structures at Gordion, central Anatolia. The Old set comprises decades centered on relative rings 777–987. The Young set comprises decades centered on relative rings 1325–1754. Radiocarbon measurements were carried out at Heidelberg according to standard procedures (*42, 43*). Data shown here and used in this study include a small additional error factor determined from a detailed intercomparison of measurements by the Heidelberg and Seattle laboratories on mid–second millennium B.C. south German oak of known age (*12*); total stated errors are thus regarded as conservative.

here on a program of high-precision radiocarbon dating and analysis aimed at testing the date placement we proposed in 1996 (*4*). We find that our former position is no longer tenable against these new data and propose an upward revision of the date by some 22 years.

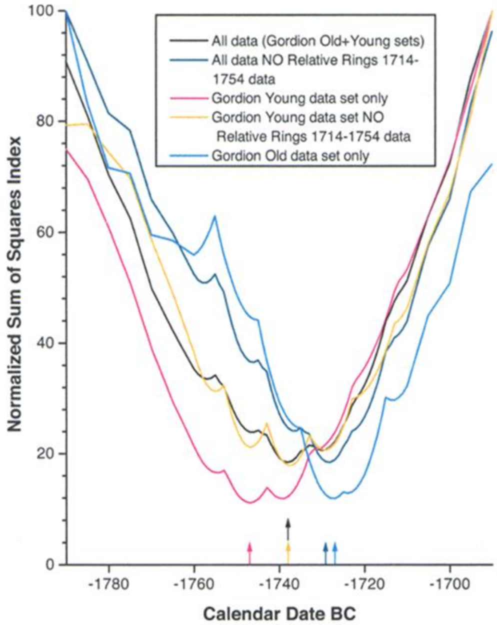

Fig. 2. Sum of least squares best (minimum) fits for the Gordion radiocarbon data against the standard internationally recommended INTCAL98 radiocarbon calibration data set (*6*). All data are shown in terms of the fit calculated for relative ring 777 of the tree ring chronology. The sum of squares of differences data are normalized, so that the maximum value for each fit function sequence shown in the figure, is 100. The specific best fit year for each data set is indicated by the arrow. Annual data are shown for 1760–1710 B.C. data points, with 5-year points on either side of the main fit zone.

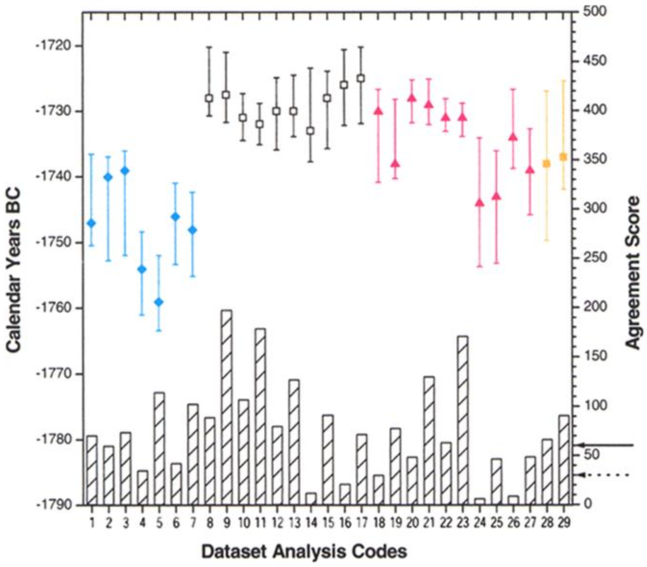

Fig. 3. 2σ 95.4% confidence best fit ranges, with symbols indicating the specific best fit year, for the defined sequence Gordion data sets [Gordion Young, Gordion Old, and "all" (Gordion Young + Old combined)] against a range of high-precision radiocarbon measurements on wood of known age using the OxCal software (*10*). Key to symbols used: cyan diamonds, Gordion Young data set only; open black squares, Gordion Old data set only; magenta triangles, all data (Gordion Old + Young data sets); yellow squares, Gordion Young data set minus measurements centered on relative rings 1714 to 1754. The total statistically viable range of possible best fits from the extremes of the 2σ fits from all calibration data sets lies between 1720–1736 B.C. (data points 8 through 17, not including data point 14). 3σ 99.7% confidence ranges are only very slightly larger: for example, for data point 20 above the 3σ range is 1734–1722 B.C., versus 1732–1725 B.C. at 2σ. The OxCal-calculated agreement scores for each fit are shown at the bottom, with scale to the right. Larger values indicate better agreement. Fits indicated for data points 14, 24, and 26 fail a 95% level χ^2 test and are thus unsatisfactory. Outliers were arbitrarily defined as data with individual OxCal agreement scores of <30%, indicated by the dotted arrow on the right (half the nominal general satisfactory test level of 60%, indicated by the solid arrow on the right). The key to the data shown is as follows: 1 = Gordion Young set versus (*6*); 2 = Gordion Young set versus (*7*); 3 = 2 minus outliers; 4 = Gordion Young set versus (*8*); 5 = 4 minus outliers; 6 = Gordion Young set versus (*9*); 7 = 6 minus outliers; 8 = Gordion Old set versus (*6*); 9 = 8 minus outliers; 10 = Gordion Old set versus (*7*); 11 = 10 minus outliers; 12 = Gordion Old set versus (*7*) modified by data in (*12*); 13 = 12 minus outliers; 14 = Gordion Old set versus (*8*); 15 = 14 minus outliers; 16 = Gordion Old set versus (*9*); 17 = 16 minus outliers; 18 = all data (Gordion Young + Old) versus (*6*); 19 = 18 minus outliers; 20 = all data minus rings 1714–1754 versus (*6*); 21 = 20 minus outliers; 22 = all data minus rings 1714–1754 versus (*7*); 23 = 22 minus outliers; 24 = all data minus rings 1714–1754 versus (*8*); 25 = 24 minus outliers; 26 = all data minus rings 1714–1754 versus (*9*); 27 = 26 minus outliers; 28 = Gordion Young set minus rings 1714–1754 versus (*6*); 29 = 28 minus outliers.

In order to refine the placement of this chronology, we made high-precision radiocarbon measurements on 52 decade samples cut from tree rings in the floating chronology "Gordion Old," from approximately the 17th to 16th centuries B.C., and "Gordion Young," from approximately the 12th to the 8th centuries B.C. (*5*) (Fig. 1). The Gordion Old and Young tree ring sets were then compared with high-precision radiocarbon measurements made on absolutely dated tree rings from Europe (southern Germany and the north of Ireland) for the relevant period (*6*–*9*), both with the OxCal software employing a Bayesian probability approach (*10*) and through the sum of least squares best correlations (Figs. 2 and 3). Two interesting and important problems became evident. First, the best fits calculated for the Gordion Young and Old sets independently, against the standard internationally recommended INTCAL98 radiocarbon calibration data set (*6*), yielded date fixes for the overall dendrochronology that differed by ~20 calendar years. Moreover, the Gordion Young data set did not exhibit a very good agreement statistic (even with outliers excluded), in contrast to the Gordion Old set. Second, separate comparisons of the Gordion Young data set against each of the two components that are combined to form the standard INTCAL98 data set {Seattle laboratory data on German oak (*7*) and Belfast laboratory data on Irish oak (*8*) [contrast (*9*), but see (*11*) disputing corrections made in (*9*)]} show a further marked discrepancy of up to ~20 calendar years, whereas the Gordion Old data set offers a narrow fit range, whichever calibration series is employed.

This discrepancy requires explanation; the secure internal nature of the tree ring chronology requires that the two dated sections offer consonant results. Elsewhere we have compared the radiocarbon ages of known age A.D.–period Anatolian pine with German oak and, over a 250-year period, found on average no measurable offset (*12*). This is consistent with modeling and observation, which suggest, on average, that regional atmospheric radiocarbon variations within the mid-latitude zone of the Northern Hemisphere are small [~1 per mil (‰)] and, in effect, are below best current high-precision measurement levels (*13*, *14*). This lack of any measurable offset is consistent with what we have observed in the Gordion Old data set. However, the demonstrated discrepancy and variation in the Gordion Young set can be explained, we suggest, by a time-dependent regional difference in $^{14}CO_2$ uptake; that is, the demonstrably different real radiocarbon ages of samples from different Northern Hemisphere latitudes and regions (due to regional uptake of seasonally varying $^{14}CO_2$ levels) during the short period of very rapidly changing radiocarbon levels from the mid-9th through the mid-8th centuries B.C. associated with a short-term episode of marked atmospheric cooling and reduced solar input (*15*, *16*). A hypothetical mechanism to explain this phenomenon is discussed in a companion report in this issue of *Science* (*12*). The offset for the mid-9th through mid-8th centuries B.C. is apparent between the Belfast laboratory measurements on Irish oak (~55°N) and the Seattle laboratory measurements on German oak (~50°N) (Fig. 4, inset). We believe that the wood from further south in Anatolia (~40°N) exhibits a similar but even more pronounced trend during this period.

We thus argue that it is no coincidence that the best date for the overall Anatolian tree ring chronology required by the Gordion Old data set, which places the five Gordion Young data centered on relative rings 1714–1754 in the early 8th century B.C., should find these 5 measurements—alone of the 52 measurements—exhibiting a clear and consistent older radiocarbon age offset from the radiocarbon measurements made on both German and Irish wood (Fig. 4 and inset). Discounting these five measurements allows the overall combined Gordion Old + Young sequence to find its best correlation within less than three calendar years of the Gordion Old fit against either the INTCAL98 data set or the Seattle measurements on German oak (Figs. 2 and 3). It also sufficiently shifts the 2σ OxCal best fit range of the Gordion Young set against the INTCAL98 data set to overlap with the equivalent 2σ fit range for the Gordion Old set (Fig. 3, data points 8 and 9 versus 28 and 29).

We propose that the best current date for the floating Anatolian Bronze-Iron Age tree ring chronology is achieved by using only the Gordion Old data set, which avoids the early 8th-century B.C. regional radiocarbon offset issue (*12*) and, with reference to the INTCAL98 data set, offers the best correlation (agreement) (Fig. 3, data point 9). This places relative ring 777 at either 1728 or 1727 B.C. (with or without outliers, respectively) against the INTCAL98 standard (Figs. 2 through 4); we select 1727 B.C. (Fig. 2). Reference to the other radiocarbon calibration data sets available for the period offering statistically consistent correlations indicates a range of best fits for relative ring 777 from 1732 to 1725 B.C., based on the Gordion Old data set (Fig. 3, data points 8 through 17, not including data point 14). Allowing for other uncertainties (*17*), a date for relative ring 777 of 1727 +4 or –7 (+4/–7) B.C. therefore appears to be a reasonable best estimate on the basis of present data.

The revision raises the date of the entire floating Anatolian Bronze-Iron Age tree ring chronology by ~22 +4/–7 years. This has important implications for the nexus of buildings, sites, regnal years of named kings/administrators, and events that are linked to the tree ring chronology and so dated by it. We believe that the new dating in fact conforms better to external corroborative evidence where available. For example, cutting dates for major timbers from the ongoing excavations of Altan Çilingiroğlu at Ayanis from a temple of Rusa II dedicated to the god Haldi, and placed in the earlier part of the reign of this last great king of Urartu, are now placed circa (ca.) 677–673 +4/–7 B.C., which corresponds well with the approximate dates for Rusa II of ca. 685–645 B.C. derived through textual and inscriptional synchronisms with the historical Neo-Assyrian chronology (*18*, *19*).

We note the following key revisions to synchronisms discussed previously (*4*). The dates for the construction of the Sarıkaya Palace at Acemhöyük and the Waršama Palace at Kültepe (Karum Kaneš Ib) may now be dated ca. 1774 +4/–7 B.C. and ca. 1832 +4/–7 B.C., respectively. The latter palace was in use for at least 61 years, as determined from the presence of later dated repair timbers. Prosopographical references on clay bullae found in these buildings (*20*–*24*) allow us to resolve more than a century of debate over a problematic 300-year range in Assyrian-Mesopotamian chronology between Ultra-High, High, Middle, Low, and Ultra-Low options (*24*, *25*). Sealings of Šamši-Adad I, the Old Assyrian King, and of his officials are found in an archive collection from the Sarıkaya Palace at Acemhöyük and must postdate its construction ca. 1774 +4/–7 B.C. Some of the earliest documents from Kültepe Ib are also associated with Šamši-Adad I, and officials from the later part of his reign are subsequently attested in the Karum Kaneš–Aššur correspondence. The implication is that the beginning of Kültepe Ib was around, or a little before, the accession of Šamši-Adad I and that at least the later part of his reign was contemporary with a post–ca. 1774 +4/–7 B.C. date at Acemhöyük. Šamši-Adad I was a king for a minimum of 57 years, the latter 33 of these as king of Assyria (*23*). With the revised Anatolian tree ring dating, only a chronological solution close to the classic Middle Chronology, which places the reign of Šamši-Adad I between ca. 1832 +7/–1 B.C. and 1776 +7/–1 B.C., is viable (*26*). The so-called low-Middle chronology is also plausible. The High Chronology, some 56 years earlier, is ruled out, and the Low Chronology, some 64 years lower, or recent Ultra-Low proposals (*25*), some 89 years lower, are rendered respectively unlikely and very unlikely, as these options would require long pre–Šamši-Adad I phases for both contexts, but there is no pre–Šamši-Adad I documentation in either context, despite much epigraphical and glyptic evidence.

The core of the Bronze-Iron Age Anatolian dendrochronology is built from timbers from a variety of contexts at Gordion. The trees used to build the burial chamber in the great Midas Mound Tumulus [perhaps the burial place of the legendary king (*2*, *27*) or one of his ancestors] were cut in ca. 740 +4/–7 B.C. The last preserved ring from construction timbers in Terrace Building 2A, the context at Gordion with the second-best sampling after the big tomb, is now dated ca. 883 +4/–7 B.C., a date we believe approximates construction of this building, which was destroyed in a conflagration between 830 and 800 B.C. (*28*), thereby helping redefine the chronology for the early phases of the Phrygian capital.

In the Anatolian dendochronology from the second millennium B.C., there is a unique and extraordinary growth anomaly starting in rela-

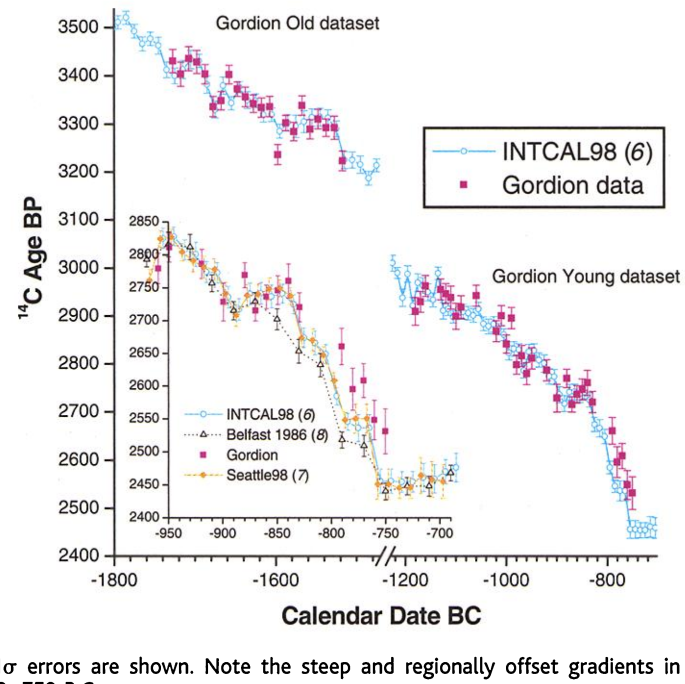

Fig. 4. Proposed best fit for the Gordion radiocarbon ages from the Old and Young tree ring data sets against the standard internationally recommended INTCAL98 data set (*6*). 1σ 68.2% confidence errors are shown. Relative ring 777 is placed at 1727 +4/–7 B.C. (Inset) Comparison of radiocarbon ages on wood of known age from (i) Belfast laboratory on Irish oak (*8*), (ii) Seattle laboratory on German oak (*7*), (iii) the internationally recommended INTCAL98 combination of Seattle and Belfast data (for this period) (*6*), and (iv) the Gordion data at the proposed best fit (main graph). 1σ errors are shown. Note the steep and regionally offset gradients in radiocarbon ages ca. 850–750 B.C.

tive ring 854 and lasting about 3 to 5 years, represented now in 61 trees of three species (juniper, cedar, and pine) from the site of Porsuk/Ulukışla (*4*, *29*, *30*). In 1996, we suggested that this anomaly might have been caused by the impact of the great eruption of the relatively proximate volcano of Thera (Santorini); we continue to regard this as the most likely explanation. Recent evidence and discussion imply that the eruption caused a greater regional impact and short-term climate effect than previously estimated (*29*, *31*, *32*). Ring 854 now dates ca. 1650 +4/–7 B.C. This date may offer a correlation with the large volcanic signal noted in Greenland ice cores ca. 1645 ± 7 B.C. (*33*, *34*). This signal has a demonstrable origin in the low to mid–Northern Hemisphere (versus high northern latitude), and no very large Southern Hemisphere eruption is attested at this time (*35*). It has previously been suggested that the signal represents the Thera eruption (*29*, *33*, *34*), and this position now appears likely to be established as correct by recent analysis of associated tephra shards (*36*, *37*). If confirmed, this would imply that in the mid–second millennium B.C. Aegean and east Mediterranean, a "high" Aegean chronology (*29*), some 100 to 150 years earlier than the conventional dating, is required.

The revised dating of the Anatolian Bronze-Iron tree ring chronology presented here is based on the best currently available data and replaces earlier statements (*38*). We have also measured south German wood of known age ourselves (*12*) and achieved an effectively identical correlation outcome, supporting the findings above based on the INTCAL98 data set (data points 12 and 13 in Fig. 3). Thus, until the floating Anatolian Bronze Age–Iron Age tree ring chronology is finally linked to a continuous sequence running from living trees backward, and so made absolute, we believe that the dating presented here offers a good near-absolute time scale for this part of the Old World.

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5. We selected 2 trees of the 41 trees recorded and cross-dated at the Midas Mound Tumulus at Gordion, which comprise a total chronology of 918 years: GOR-3 (*Juniperus excelsa*), covering relative rings 999–1764, and GOR-2 (*J. foetidissima*), covering relative rings 1279–1654. We also used one tree, GOR-161 (*J. excelsa*), from the nearby Kizlarkaya Tumulus, covering relative rings 739–1599. The total Gordion area chronology comprises 1026 years. Trees GOR-3 and GOR-161 overlap for 601 years and yield a *t* score correlation of 8.52, with the two trees reflecting in common 60.3% of all growth trends over the 601 years of overlap. The radiocarbon data comprise (i) 22 measurements from consecutive decades over 220 years centered on relative rings 777 to 987, referred to as the Gordion Old set; and (ii) 30 measurements from decades over 440 years, centered on relative rings 1325 to 1754, referred to as the Gordion Young set (nonavailability of sufficient good sample material dictated that this latter set could not be from entirely consecutive decades). The Gordion Young set incorporates and revises the section measured previously (13 of the previous 18 measurements are reused and are regarded as technically satisfactory; the remainder are revised with new measurements) (Fig. 1).
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17. The basic date fix has an approximate 2σ range of +2/–5 years (the 3σ 99.7% confidence range is only slightly larger: for example, relative ring 777 lies between 1734–1722 B.C., when all data are used minus relative rings 1714–1754). However, in addition to these uncertainties, we should also allow for potential decade mismatching (dated decade versus calibration decade). If one considers the annual radiocarbon data in (*7*) in terms of a moving decade age for the available continuous annual data sets before bomb activity [decades centered 1520–1529 to 1630–1639 and 1800–1809 to 1930–1939 (other decade intervals between these lack data for at least one individual year)], then a worst case offset of ±2 calendar years is determined with OxCal and the INTCAL98 data set, whether for the individual 12 and 14 decade or combined 26 decade series. Hence, we allow an additional ±2 calendar year error to our best fit date in the text; thus relative ring 777 = 1727 +4/–7 B.C.
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26. The date is derived from the correlation of Šamši-Adad I, year 33 as king of Assyria (his year of death), which equals his year minimum of 57 as king, with year 17 of Hammurapi of Babylon, proposed by D. Charpin and J.-M. Durand [*Mari: Ann. Rech. Interdisciplinaires* **4**, 293 (1985)]. The possible correlation range is between Hammurapi year 10 (the last Babylonian date on which Šamši-Adad I was attested as alive) and Hammurapi year 18 (accession of Zimri-Lim of Mari, with the death of Šamši-Adad I known to be previous to this). Thus, the dates for Šamši-Adad I in the text have a total error range of +7/–1 years. A recently recognized solar eclipse record in the Mari Eponym Chronicle occurs the year after the birth of Šamši-Adad I (became a king at age 18) (*39*). In conjunction with the new revised dendrochronological date fixes for Kültepe and Acemhöyük, this may allow a likely precise date range to be interpolated for Šamši-Adad I. Among other possible candidates, a prominent total eclipse of 1832 B.C. (*39*) is perhaps an interesting candidate; this would support a chronology in the range of, but some 13 to 17 years [compare data in (*24*) and (*39*)] lower than, the classic Middle Chronology.
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38. A variety of published dendrochronologically derived dates based on previous work (*4*) now require revision upward by 22 +4/–7 years. For example, of relevance to discussions of the Bronze Age–Iron Age transition, cutting dates for timbers in Late Bronze Age levels at Tille Höyük (*40*) are now ca. 1123 +4/–7 B.C., and cutting dates for timbers from early Iron Age levels at Kaman-Kalehöyük (IID) (*41*) range from ca. 949 +4/–7 B.C. to ca. 884 +4/–7 B.C. Caution should be exercised concerning a previously stated date derived from just two poorly preserved pieces of cargo/dunnage wood from the famous Uluburun shipwreck (*4*, *29*). The quality and security of the dendrochronological placement of these samples versus the Bronze-Iron master chronology are not especially strong. If the fit is confirmed, the last preserved ring would now lie ca. 1327 +4/–7 B.C. This would confirm the conventional chronology of ancient Egypt, because the presence of a gold scarab of Nefertiti on the ship requires her standard mid–14th century B.C. data range.
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