Anatolian tree rings and the absolute chronology of the eastern Mediterranean, 2220–718 BC

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EXCELLENT preservation of wood and charcoal at archaeological sites in Anatolia has allowed the Aegean Dendrochronology Project to build absolute and floating tree-ring sequences[1]. One such floating dendrochronology of 1,503 years includes samples relating to known rulers, sites and cultures of the ancient eastern Mediterranean. If this chronology could be dated precisely, many long-standing questions might be resolved. Here we report 18 high-precision ^{14}C determinations which, when wiggle-matched to the radiocarbon calibration curve, provide a date within narrow limits. Inside this range, we can suggest the probable absolute dating of the dendrochronology because of a remarkable growth anomaly in the seventeenth century BC, for which we propose a correlation with major growth anomalies at 1628/1627 BC in the absolutely dated dendrochronologies of Europe and the United States. Many archaeological sites from several cultures in the eastern Mediterranean can now be dated with fine precision. This chronology has important implications for Old World archaeology and prehistory.

A tree-ring chronology of 1,503 years has been constructed from large groups of timbers in major archaeological monuments, principally at Gordion, Porsuk, Acemhöyük and Kültepe in Anatolia[2], and might provide a solution to many currently impenetrable or ambiguous issues in eastern Mediterranean archaeology. However, this prehistoric chronology is floating, that is, it is not connected at present to a fixed dendrochronology from living trees backwards.

We have dated this chronology by obtaining high-precision ^{14}C determinations on a sequence of decadal samples from it, and matching the results with the precisely dated decadal variations in radiocarbon ages known for European wood (Table 1; Figs 1 and 2). A placement of the end of the 350-year radiocarbon-dated sequence at ~820 BC is most likely (with an estimated 2σ, 95.4%, confidence error of +76/−22 calendar years). The entire 1,503-year dendrochronology[2] thus begins at 2233 BC and runs to 731 BC (+76/−22 years).

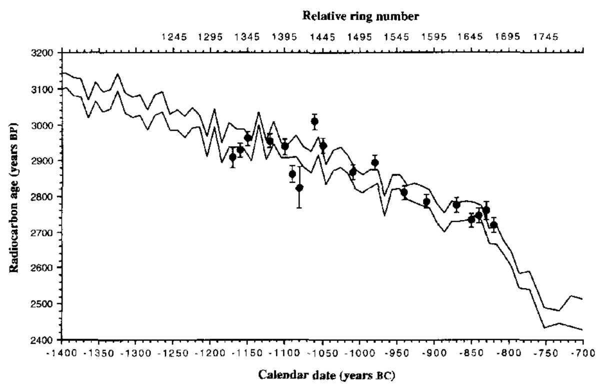

FIG. 1 Wiggle-match (best fit) of the 18 dendrochronologically sequenced ^{14}C measurements (Heidelberg data) (1σ error bars shown) against the 1993 decadal radiocarbon calibration curve (1σ confidence band)[25]. The 350-year dated sequence (relative rings 1325 to 1675) begins at 1170 BC and ends at 820 BC. Estimation of the error on the above fit is problematic. It should include: (1) the combination of the measurement errors on the Heidelberg data and the calibration curve (18 paired measurements, which yields ± 8 ^{14}C years); (2) the likely systematic laboratory offset between Heidelberg and the relevant calibration laboratory (Seattle), estimated as $\pm \leq 20$ ^{14}C years (from intercalibration of identical wood samples between the Seattle and Heidelberg laboratories; M. Stuiver, personal communication; B. Kromer, personal communication); (3) the error from the potential mismatching of the specific decades dated at Heidelberg versus those dated for the calibration curve (estimated as $\pm \leq 15$ ^{14}C years, from analysis of ref. 25); and (4) the possibility of small regional differences in ^{14}C levels[27,28], which between central European oak and central Anatolian juniper we estimate as $\pm \leq 15$ ^{14}C years. (This is a highly speculative issue which we address by specifically using calibration data based on wood (central Europe) growing nearest to Anatolia, and without major ocean input or extreme altitude difference. Further, even in the claimed cases[27,28] of differences between sequoia from the west coast of the United States and Irish oak, and Irish oak and German oak, a dominant contribution from laboratory offsets and measurement errors cannot be excluded.) Therefore an overall combined error of $\pm \leq 30$ ^{14}C years exists on our wiggle-match at 1σ confidence. Conversion of this ^{14}C-year confidence interval onto the calendar scale is asymmetrical, as the shape of the radiocarbon calibration curve constrains the lower limit much more than the upper one. We estimate the fit as +76/−22 calendar years at 2σ, 95.4%, confidence.

TABLE 1 Radiocarbon dates for 10-year samples of juniper

Relative ring/year	^{14}C age (BP $\pm\sigma$)	χ^2 best fit, date (BC)	OxCal 68.2% confidence date (BC)	OxCal 95.4% confidence date (BC)
1675	2720 ± 20	820	818–826	814–840 ($P = 0.86$), 847–853 ($P = 0.14$)
1665	2760 ± 25	830	828–836	824–850 ($P = 0.86$), 857–863 ($P = 0.14$)
1655	2746 ± 20	840	838–846	834–860 ($P = 0.86$), 867–873 ($P = 0.14$)
1645	2734 ± 20	850	848–856	844–870 ($P = 0.86$), 877–883 ($P = 0.14$)
1625	2777 ± 20	870	868–876	864–890 ($P = 0.86$), 897–903 ($P = 0.14$)
1585	2786 ± 20	910	908–916	904–930 ($P = 0.86$), 937–943 ($P = 0.14$)
1555	2811 ± 20	940	938–946	934–960 ($P = 0.86$), 967–973 ($P = 0.14$)
1515	2895 ± 20	980	978–986	974–1000 ($P = 0.86$), 1007–1013 ($P = 0.14$)
1485	2868 ± 20	1010	1008–1016	1004–1030 ($P = 0.86$), 1037–1043 ($P = 0.14$)
1445	2942 ± 21	1050	1048–1056	1044–1070 ($P = 0.86$), 1077–1083 ($P = 0.14$)
1435	3009 ± 23	1060	1058–1066	1054–1080 ($P = 0.86$), 1087–1093 ($P = 0.14$)
1415	2825 ± 59	1080	1078–1086	1074–1100 ($P = 0.86$), 1107–1113 ($P = 0.14$)
1405	2863 ± 23	1090	1088–1096	1084–1110 ($P = 0.86$), 1117–1123 ($P = 0.14$)
1395	2938 ± 23	1100	1098–1106	1094–1120 ($P = 0.86$), 1127–1133 ($P = 0.14$)
1375	2955 ± 20	1120	1118–1126	1114–1140 ($P = 0.86$), 1147–1153 ($P = 0.14$)
1345	2962 ± 20	1150	1148–1156	1144–1170 ($P = 0.86$), 1177–1183 ($P = 0.14$)
1335	2929 ± 20	1160	1158–1166	1154–1180 ($P = 0.86$), 1187–1193 ($P = 0.14$)
1325	2909 ± 28	1170	1168–1176	1164–1190 ($P = 0.86$), 1197–1203 ($P = 0.14$)

^{14}C measurements (18) of 10-year samples of juniper from one log, crossdated with 40 other timbers for its entire length, from the Midas Mound tumulus at Gordion (Heidelberg data). The samples are from relative rings/years 1320–1330 to 1670–1680 (the whole 1,503-year chronology runs from relative rings/years 262 to 1764); the ^{14}C determinations are regarded as belonging to the midpoint of each dated decade. The sequence of data was then matched to the 1993 decadal radiocarbon calibration curve[25]. This data set was selected because: (1) its resolution most closely corresponds to that of our data; (2) it reflects the most accurate estimate of atmospheric radiocarbon variations in the age range of our chronology; and (3) the data are from trees that grew in central Europe, so they are the most compatible and representative available for wood from Turkey. The data were best-fitted to the calibration curve by using two computer programs: a chi-squared, least-squares difference, procedure[21], and a probability procedure (OxCal 2.18)[26]. From the former, at 95.4% confidence, the midpoint of the most recent dated decade belongs between 894 BC and 789 BC. More specifically, the best fit is at 820 BC (see Fig. 2). The OxCal program suggested that four measurements were potentially inconsistent based on quoted errors (at rings 1325, 1405, 1415 and 1435), with the data for rings 1405 and 1435 less consistent than rings 1325 and 1415. If all 18 data are used, the OxCal 95.4% confidence range for the end date of the sequence is 814 BC to 840 BC ($P = 0.86$) and 847 BC to 853 BC ($P = 0.14$) (at 68.2% confidence: 818 BC to 826 BC). If only the best 16 data are used: 816 BC to 842 BC ($P = 0.94$) and 847 BC to 853 BC ($P = 0.06$) (at 68.2% confidence: 821 BC to 829 BC). If the best 14 data are used: 815 BC to 875 BC (at 68.2% confidence: 820 BC to 829 BC ($P = 0.64$) and 846 BC to 850 BC ($P = 0.36$)).

Within the dating 'window' established independently by the radiocarbon evidence, we believe we can provide an even more precise date for the dendrochronology. In 36 trees from the site of Porsuk in south-central Anatolia[3], with tree rings dated to the 17th century BC by the radiocarbon wiggle-match, there is an exceptional growth event at and immediately following relative ring 854 (~1,641 +76/−22 BC from the wiggle-match) (Fig. 3). In dendrochronologies from Europe and the United States, a similar dramatic, cooler, wetter climatic event is also recorded in the 17th century BC, absolutely dated at 1628/1627 BC[4,5]. As in the Anatolian tree-ring chronology, this event is unusual, and is the only such event in the 18th–15th centuries BC. It correlates with evidence from Greenland ice cores of a major volcanic eruption and other data reflecting a major climatic/atmospheric anomaly[5,6]. The year 1628 BC can be regarded as a special marker event in Northern Hemisphere tree-ring chronologies[5].

We propose that the Anatolian ring 854 event be correlated with the events of 1628/1627 BC in Europe and the USA, because it is compatible with the date range established by the radiocarbon wiggle-match. We find support from a second coincidence: 470 years after the ring 854 event, another growth anomaly (significant but much smaller than that of the 17th century BC) begins at ring 1324 in the Anatolian dendrochronology[7]. This provides a very good match (±0–1 year) with the major anomaly commencing in

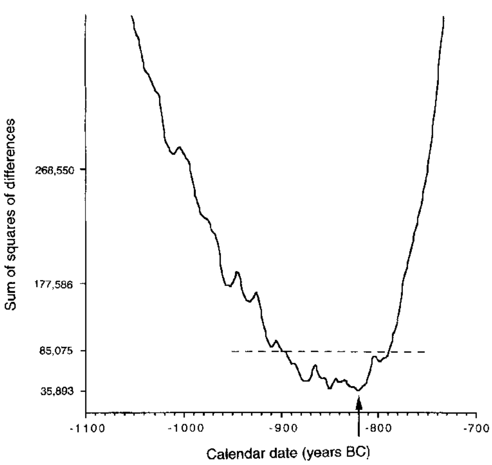

FIG. 2 The chi-squared fit function (based on sum of squares of differences) for the wiggle-match of the 18 dendrochronologically sequenced ^{14}C measurements (Heidelberg data) against the 1993 decadal calibration curve[25] (cubic spline through data points to produce an annual curve) shown in terms of the fit of the end date for the 350-year dated sequence (decades from relative rings 1320–1330 to 1670–1680; date regarded as the midpoint of each decade). The best fit is at 820 BC (arrow; $\chi^2 = 12.36$) (and generally ± about two decades). A fit around 850 BC is also possible, but less likely. The OxCal 2.18 data (see Table 1) reflect this same potential ambiguity: a region around 820 BC is most likely, although a lesser possibility exists around 850 BC. The fit is good, but by no means perfect. It would be desirable to date down the steep slope in the radiocarbon calibration curve 820 BC–750 BC, but there is insufficient sample material for high-precision dating from the Anatolian dendrochronology. However, a perfect fit should not be expected: even the best high-precision radiocarbon laboratories exhibit small systematic offsets from each other[27,29]. The broken line indicates a 95% significance level; $\chi^2 = 27.59$, 17 d.f.; the fit is therefore between 894 BC and 789 BC.

1159 BC known from Europe[5]. This is the only such important event for several centuries in either chronology. This 1159 BC event is linked to the eruption of Hekla 3 in Iceland, as attested in ice-core data from Greenland[5]. The very high latitude of this volcano, and the strong poleward transport of atmospheric circulation, explains the reduced impact in Anatolia and the lack of evidence for a large effect (frost damage) in the White Mountains of California.

The combination of high-precision radiocarbon wiggle-matching and the correlation of dendro-marker events offers a likely absolute date for the 1,503-year chronology from Anatolia. The anomalies from the 17th and 12th centuries BC probably result from large, climatically effective, volcanic eruptions, the resultant aerosol forcing atmospheric cooling for a few years[4,5]. Evidence for suitable, large volcanic eruptions is found at these times in Greenland ice cores[5,8,9]. Correlation of the few major common events in the tree-ring and ice-core chronologies allows the specific identification of an important volcanic event at 1628 BC[5,6,10,11].

The exceptional growth of relative ring 854 is continuous in both early and late wood, so the responsible climate-modifying event (the volcanic eruption) must have occurred immediately before the beginning of spring growth. The event/eruption shows up in the spring of 1628 BC in Ireland and then, as temperatures in the northern hemisphere drop as a result of aerosol forcing, as frost damage in 1627 BC in California at the upper timber line. An eruption date in late 1629 BC (after the growing season) or early 1628 BC is likely. Thus ring 854 of our 1,503-year chronology relates to 1628 BC.

This new chronology is of wide significance. A nexus of buildings, sites, personages and events may now be directly and precisely dated. The chronology dates 22 major sites, ending with the cutting of trees for the Midas Mound tumulus at Gordion in 718 BC. For example, the Sarıkaya Palace at Acemhöyük has wall footings of juniper and cedar that were cut (bark present) in 1752 BC, and the Waršama Palace at Kültepe was built in 1810 BC. Because documents preserved on clay in these buildings provide links with rulers from Assyria and Syria[12], the new fixed dendrochronology provides important evidence towards the resolution of a century of debate over Assyrian and Mesopotamian chronology. In particular, it renders the so-called High chronology very unlikely, and supports either a Low or lower-Middle chronology (or a new independent chronology in this range). Wood found as part of the cargo on the Kaş/Uluburun shipwreck[13] has a last preserved ring of 1316 BC; other finds include Mycenaean pottery from Greece (the most recent material present is early Late Helladic IIIB; J. B. Rutter, personal communication), and a unique gold scarab of Nefertiti, wife of Akhenaten, pharaoh of Egypt[14]. These provide links to the chronologies and histories of the Aegean and Egypt, and confirm conventional 14th–12th century BC chronology[14,15] against recent radical critiques[16]. Tree-ring dating now offers the route to a new, absolute, chronology of the Old World that is independent of existing assumptions, gaps in evidence, and debates.

The specific identification of the large volcanic eruption responsible for the 1628 BC climate event has implications for several recent controversies. The main candidate for the 1628 BC event has been the Minoan eruption of the volcano of Santorini/Thera in the Aegean, although other eruptions have been proposed[17,18]. Arguments against Thera's candidacy have been based on petrological evidence suggesting that its SO_2 production was too small to account for either dramatic atmospheric cooling or the large H_2SO_4 peaks in the 17th century BC record in Greenland ice cores[17–19]. These arguments can now be dismissed, because it is clear that petrological analysis seriously underestimates SO_2 emissions[5,20,21]. In addition, none of the other suggested eruptions is as well dated as Thera, nor as compatible with a date in the 17th century BC[21]. The eastward distribution of volcanic products from the Thera eruption[19] is consistent with a spring eruption (and thus the winter–spring date of the 1628 BC climate event). The 17th century BC growth event in the Anatolian trees was much more dramatic and clearly defined than any other growth anomaly in 6,500 years of Aegean tree-ring chronologies, including those (similar but much smaller) events that might be linked with other known large, climatically effective, volcanic events. There is likely to be a specific and local cause: the massive volcanic eruption of Thera just 840 km west of Porsuk. We suggest this as the working hypothesis; definitive confirmation must await the identification of Thera eruption products in a dated ice core, as has now been achieved for several more recent eruptions[22].

If sustained, a date of 1628 BC for the Thera eruption will require a major revision of Aegean chronology at the beginning of the Late Bronze Age, raising the date of the eruption, and the associated Minoan, Mycenaean and Cycladic archaeological phases, from ~1500 BC to 1628 BC[23]. Sets of material and stylistic linkages between the Aegean, Cypriot, Levantine and Egyptian cultures[11,23,24] mean that this revision will lead to large changes in Old World chronology and history in the 18th–15th centuries BC. Longstanding assumptions and conventions in both Egyptian and Old World chronology and history will need to be re-examined. □

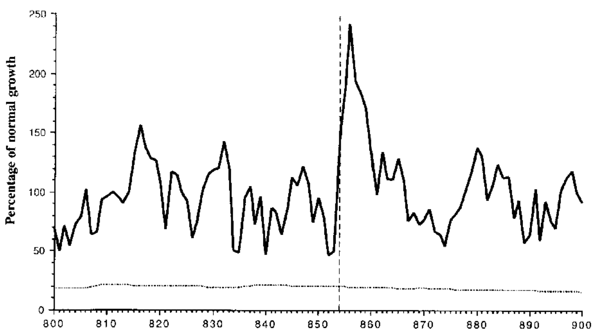

FIG. 3 In relative year 854 (shown by the vertical dashed line) a population of juniper trees (number of samples shown by dotted line, variously 15–21) ranging in age (in relative ring/year 854) from 19 to at least 143 years experiences a sudden growth event. This is also reflected in cedar and pine trees from the site (total number of samples, 36; ages overall, 19 to >244 years at the time of the growth event). As a group, the average percentage growth among the juniper trees reaches 241.6% of normal (determined against a 20-year moving average) in relative year 856. Individual juniper trees put on annual rings from 250% to 739% of normal growth. These dramatic variations are without parallel in the 6,500 years of Aegean dendrochronologies. In this geographical/climatic area, such an exceptional growth event must be due to unusually high and sustained soil moisture content and a sharp reduction in midsummer evapotranspiration[30]; that is, for a short time there was unusually cool and wet weather. The significantly varied ages of the trees at the time of the growth event (19 years to >244 years), the specific, short-lived and highly unusual pattern of spring and summer growth, and the exceptional nature of the event in 6,500 years of Aegean chronologies, combine to suggest that it cannot be the result of a specific micro-environmental cause, such as insect attack, regional geomorphological change, or saplings from a single stand of trees forcing their way up through the forest canopy and growing without restraint. Instead, the cause must be a macro-environmental event, resulting in unusual hemisphere-wide cooler and wetter weather.

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