Anatolian tree-ring studies are untrustworthy

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The chronology of the Ancient Near East is poorly understood. Although many references give exact dates for events, such as the building of the Great Pyramid or the rise of certain kings in Babylon, in reality such dates are debated. Wood has the potential to resolve such debates. Many ancient buildings and other artefacts were constructed from wood, and in some circumstances, it is possible to precisely date this wood, by examining the pattern of its tree rings. Work on dating wood from the Ancient Near East has been done primarily in Anatolia (roughly, modern Turkey). This work has been conducted over many years and been published in respected journals; it has claimed to provide definitive dates for several important events in the early history of civilisation. Herein is reviewed some of this wood-dating research. The primary conclusion is that the research has invalidating flaws, which are obvious upon inspection. The underlying issue is that the system under which tree-ring research generally is conducted lacks transparency.

1. Introduction

Most trees grow a tree ring each year. The thickness (and density, etc.) of tree rings varies from year to year, and is dependent upon the local climate, ecology, and other factors [Schweingruber, 1996]. Trees live for many years, and the tree rings grown over those years then form patterns, as shown in Figure 1. The figure displays cross-sections from three trees. Imagine that the A rings are from a living tree. Hence the outermost ring (next to the bark) was grown in the last year, the ring next to that was grown the year before, etc. Imagine too that the B rings are from a dead tree, which was found in a field. We do not know a priori the years in which this tree grew, but by matching the outer rings from B with the inner rings from A, we can determine this. Suppose the C rings are from a timber used in a building. The outer rings from C can be matched with the inner rings from B; thus we can determine when the C tree grew. The building must have been constructed after the C tree grew. Hence our tree-ring matching has given us information about the time of the building's construction.

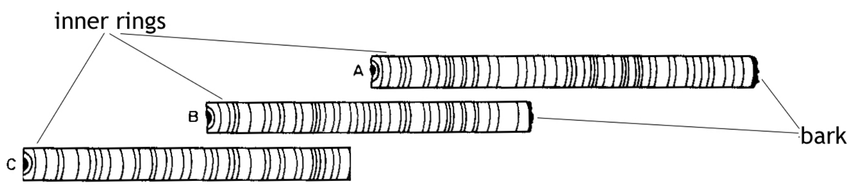

Figure 1. Schematic example of tree-ring matching.

An important goal in tree-ring studies is to build up overlapping tree-ring sequences, extending from the present to the distant past—Figure 1 illustrates. Usually, there will be several trees that grew rings for a particular year; an average ring-width for each year is then calculated. A series of such average ring widths that spans many years is called a "master dendrochronology" for the site at which the trees grew (from Greek, *dendron* = tree and *chronos* = time). Constructing a master dendrochronology for a site is essential for tree-ring dating of wooden artefacts from the site and surrounding area.

The chronology of the Ancient Near East—oftentimes called the "cradle of civilisation"—is not well established. Although many references give exact dates for events, such as the building of the Great Pyramid or the rise of certain kings in Babylon, in reality such dates are debated [James, 1991; Cryer, 1995; Rohl, 1995; Bietak, 2003]. Tree-ring dating has the potential to resolve such debates. There is currently only one (substantial) master dendrochronology from anywhere in the Ancient Near East. Hence this master dendrochronology has great importance. This master is from Anatolia.

"Anatolia" is a geographical term, roughly designating modern Turkey: see Figure 2. A master dendrochronology for Gordion (39.7 °N, 32.0 °E), in central Anatolia, was first developed in the 1970s. This master dendrochronology, however, does not extend continuously from the present to the past. (The situation is similar to what would happen if we had only the B and C rings in Figure 1. That is, we can match the B and C rings against each other, but this does not give us the date of any ring.) The master has been anchored in time—i.e. dated—largely via radiocarbon [Manning et al., 2001; Kromer et al., 2001] (originally, the master was dated via archaeo-history).

In what follows, much of the work that has been done in Anatolian tree-ring matching is reviewed. The conclusions are disturbing, and have implications for tree-ring studies generally.

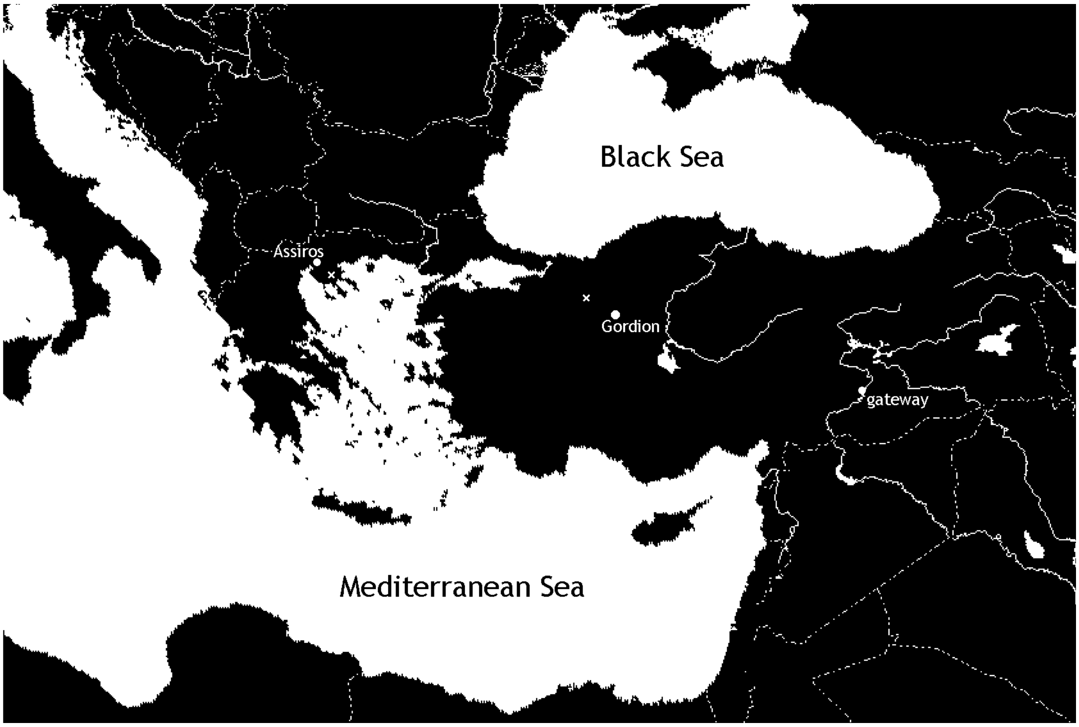

Figure 2. Map showing Anatolia. Anatolia is the large peninsula between the Black Sea and the Mediterranean Sea (constituting most of modern Turkey). In central Anatolia lies Gordion—where Alexander The Great famously cut the Gordion knot. Assiros (in Greece) and the two sites indicated by crosses are discussed in Section 7. The gateway is discussed in Section 4, and elsewhere.

2. Matching tree rings

No two trees will have exactly the same ring pattern, particularly when grown at different locations. Deciding where two ring patterns match (as illustrated in Figure 1) can be problematic, in practice. The approach to solving this problem in the pre-computer age was to rely on the skill of an experienced investigator. Nowadays, although investigator skill continues to be crucial, tree-ring matching also heavily relies on statistical methods.

Generally, an investigator will try to confirm a statistical match by visually comparing the physical rings in wood samples. For Anatolian archaeological work, however, such visual confirmation is usually difficult or impossible, because the wood is often actually charcoal (i.e. burnt remains), and the species being compared are sometimes very different. Hence in Anatolian archaeological work, tree-ring matches are often made solely on the basis of ring-width measurements. For this reason, statistical matching is particularly important in Anatolian archaeological work.

Ideally, a statistical method should give the (statistical) confidence level of a potential match. For example, comparison of two trees might conclude that we can be 99.7% confident that their rings match (such a match would then be accepted as valid). Unfortunately, no method of calculating confidence levels of tree-ring matches is known. The three commonly-used statistical methods will be briefly described next.

The most commonly-used method for statistically matching tree rings relies on what are called "*t*-scores". (The *t*-score is detailed in most introductory statistics texts; it is closely related to the coefficient of correlation.) In principle, a *t*-score is just a way of giving a confidence level *assuming* the following:

- the ring width in one year is independent of ring widths in other years, and
- ring widths have the same normal (i.e. bell-shaped) probability distribution.

The first assumption is well known to be false (because the environment in one growing season affects the tree not only in that growing season but also in the next). Experience with the *t*-score method indicates that it can nonetheless work well, provided that it is used in a manner appropriate for tree rings. Broadly speaking, a *t*-score above 3.5 is considered to indicate a tree-ring match. A *t*-score above 5.0 would be considered as implying a certain match by most tree-ring specialists. (These levels for *t*-scores are conventional; for critical discussion of how good those conventions are, see Section 5.)

Another statistical method used in tree-ring matching relies on what I will call "*g*-scores". (The *g*-score is commonly called "*gleichläufigkeit*" [Schweingruber, 1989] or "trend".) The *g*-score is the proportion (or percentage) of years in which two trees' ring widths increased or decreased together (i.e. increased or decreased from the prior year). This method thus ignores the size of the increase or decrease. Because it ignores so much information, the *g*-score method might be expected to be less reliable than the *t*-score method. Experience at Hohenheim, Germany, where *g*-scores were previously used, seems to support this: matches were thrice found to be in error, each time after strong assertions of reliability [Baillie, 1995: ch.2; Spurk et al., 1998]. Early trials in Ireland also indicated problems, and the method was abandoned there [Baillie, 1982: p.81–82,95]. Other testing found very high *g*-scores for matches known to be incorrect [Schweingruber, 1989: p.77]. In the pre-computer age, though, *g*-scores had one advantage: being easy to calculate. They are still sometimes used, perhaps out of habit.

A third statistical method used in tree-ring matching is the "linear time series" method. Very briefly, this method is similar to the *t*-score method, except that the first assumption of *t*-scores (ring widths are independent of each other) is replaced by this:

- the ring width in one year is linearly-dependent on ring widths of prior years.

This assumption is much more realistic than the first *t*-score assumption, though still not fully accurate (because the growth mechanism of tree rings is more complicated).[1]

Among the three methods, then, the linear time series method is the best. That method, however, is not widely used in tree-ring studies. The reason for this is unclear (perhaps it is convention). The linear time series method was developed, in the 1970s, as a general tool for statistical analyses. Research papers applying it to tree rings appeared in the 1980s [Monserud, 1986; Yamaguchi, 1986; Biondi & Swetnam, 1987]. And the method is nowadays taught in first-year graduate courses at what is often considered to be the world's leading institution for tree-ring studies, the University of Arizona Laboratory of Tree-Ring Research.[2]

The statistical methods that were originally used in Anatolian tree-ring studies were *g*-scores and/or *t*-scores. This presented a difficulty, however, because trees were sometimes found to match (against the master or another tree) at several places. That is, there were multiple matches with high *g*-scores and *t*-scores, and moreover, the match with the highest *g*-score was not always the match with the highest, or even second or third or fourth highest, *t*-score. There are feasible statistics-based approaches to this difficulty (e.g. use *t*-scores alone, but very conservatively). The approach that was adopted for Anatolia, however, was to rely largely on what is called a "*D*-score".

The *D*-score does not exist in statistics. It has been used solely with tree rings. *D*-scores do not have a mathematical derivation—unlike *t*-scores, *g*-scores, and times

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[1] For a review of other assumptions that are likely to be more accurate, see e.g. Tong [1990].

[2] Notes for the Laboratory's course "GEOS 585A: Applied Time Series Analysis" are available at http://www.ltrr.arizona.edu/~dmeko/geos595e.html (accessed 2005-06-14).

series. In fact, *D*-scores were more or less just made up (in an unpublished 1987 thesis[3]), and using them to evaluate a tree-ring match turns out to be little better than rolling dice—for details, see the side box. (There are other problems with *D*-scores, not discussed here, but plain to anyone familiar with mathematical statistics. In particular, *D*-scores should correspond with significance levels (under some assumptions), just as *g*-scores and *t*-scores do. For similar comments on this, see Baillie [1995: p.20].)

Regardless of which method is used for matching tree rings, it is not always possible to match one tree against another, even if the trees grew at the same site. This is due to factors affecting individual trees at the site—e.g. placement on a hill, local canopy effects, local animal influences, genetics, etc. A master dendrochronology, though, will smooth out variations in ring widths that are due to such factors. Therefore, in general, a tree can be matched more readily against a master dendrochronology than against another tree. (A master dendrochronology is almost always constructed from a single species of tree.)

D-scores

The *D*-score combines the *g*-score and *t*-score, via the following formula.

$$gt - t/2$$

The problem here is that the above formula has no apparent meaning. Consider, for instance, the obvious formula for the area of a rectangle: *base* × *height*. This formula is not just arbitrarily chosen; rather, it can be derived and shown to have the meaning "area of rectangle". Similarly, the formula for the area of a square whose sides have length l is l^2, and again this formula is not arbitrary, but derived, and has meaning.

The same is not true for *D*-scores. The choice of $gt - t/2$ is an arbitrary one among numerous formulae that could have been chosen to combine a *t*-score and *g*-score. For example, this formula might have been chosen instead.

$$gt^2$$

There is no reason given for choosing one formula over the other. Furthermore, if the second formula had been chosen, then the wood from the gateway discussed in Section 4 would have been dated to 981 BC, rather than 1140 BC. This illustrates that the choice of the date for the wood (among dates with high *g*-scores and *t*-scores) is baseless—i.e. the date might almost just as well be chosen at random.

3. Case: the shipwreck

The master dendrochronology for Gordion was formally announced in a paper in 1996 [Kuniholm et al., 1996]. This paper also gave some dates for wood from archaeological sites—dates that were obtained by matching the wood against the master dendrochronology. The most important of those dates was perhaps for wood from a shipwreck, which was claimed to resolve some of the debate about dates. (The shipwreck was found off Uluburun, southern Turkey [Pulak, 1997].)

In 1998, some details on the shipwreck wood were published [Wiener, 1998: p.314]. It turned out that there had not been a good quantitative match against the Gordion master (by *t*-, *g*-, or *D*- scores). The wood had been dated against the Gordion master solely on the basis of visual matching—a dubious practice. The visual match is

[3] The *D*-score was first described in a 1987 thesis by B. Schmidt [Kuniholm & Newton, 1989: p.291; Kuniholm et al., 1992: n.3]. The author of the thesis has acknowledged that it has no mathematical derivation (B. Schmidt, private communication, November 2003).

shown in Figure 3. The light line represents the Gordion master; it is high for years that had wide tree rings and low for years that had narrow rings. The heavy line represents the shipwreck wood. (For comparison, other figures showing visual matches are given in the next section.) It is clear that there is not a visual match. In other words, there was no match at all. The claim that the shipwreck wood had been dated was spurious.

(The shipwreck wood comprises two pieces, which were matched against each other. The number of rings of their overlap, however, is only 23,[4] which makes the match very unreliable—for reasons discussed in sections 4–5. Reliability is further lessened because one of the pieces was likely from the ship's frame and the other was cargo [Pulak, 1997]—so there is no evidence that the two trees grew at the same location and time. Thus the claimed "match" is even worse than Figure 3 indicates.)

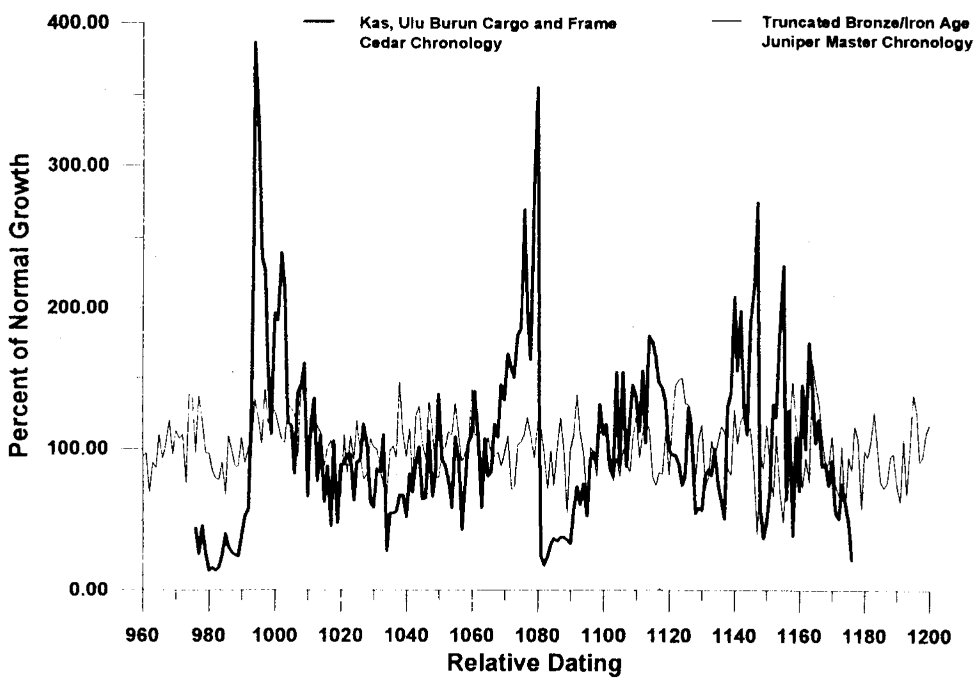

Figure 3. The shipwreck wood matched against the Gordion master dendrochronology. (This figure is given by both Kuniholm [1997: fig.7] and Manning [1999: fig.63].)

In 1999, a letter was sent to various e-mail lists, and also to the principal investigator in Anatolian tree-ring studies, pointing out some of the above (especially the statistical aspects) and concluding that there was no tree-ring match for the shipwreck wood [James, 1999]. Two years later, in the next major paper in Anatolian tree-ring studies, the tree-ring date for the shipwreck was acknowledged to be "not especially strong" [Manning et al., 2001: n.38]. The paper also claimed, though, that further work might allow the date to be "confirmed"; this claim does not seem realistic.

(In 2003, more information on the shipwreck came to light: the originally-claimed visual match was merely better than any other match "at any point fifty years in either direction" [Wiener, 2003: p.244]. Apparently, the date for the shipwreck had been narrowed to ±50 years via archaeological considerations, before attempting a tree-ring

[4] The earlier piece of wood ends 104 years before the later piece of wood [Kuniholm, 1997], and the later piece of wood has 127 rings (M.H. Wiener, private communication, April 2003).

match.[5] Despite this, the claimed tree-ring match had been proclaimed by the investigators to be conclusive evidence that dates for events in the Ancient Near East could not possibly be in error by over a century (as some researchers have argued).)

4. Case: the gateway

In order to ensure that a tree-ring match is reliable, it is typically necessary for the tree being matched to have at least 100 rings of overlap with the master dendrochronology (see further sections 5–6). Severe problems can arise when there are fewer. An example from Ireland will illustrate this (described by Baillie [1995: ch.3]). Several planks from a boat were securely dated against an Irish master. Attempts were also made to date one plank that had only 35 rings. As the investigator noted, “Normal practice at … most tree-ring laboratories … would have been to ignore this small piece … as intrinsically undatable”. As an exercise, however, an attempt was made. Figure 4 shows two positions where the 35-year ring pattern displayed visual agreement with an Irish master (top) and with a generalized master for the British Isles (bottom).

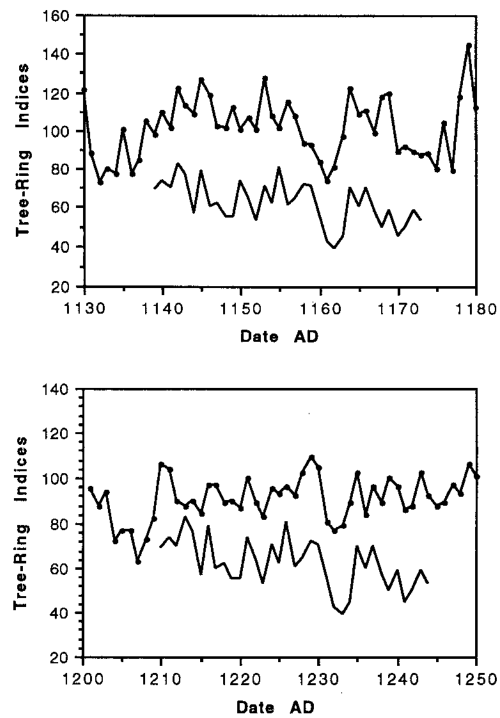

Figure 4. Examples of false matches.

As the investigator noted, these matches, especially the bottom one, are extremely good. The archaeological context, however, makes the date implied by the bottom match untenable, and the top match very unlikely. The investigator concluded as follows (emphases as in original) [Baillie, 1995: p.54–55].

> The truth is that no one can put their hand on their heart and swear to a unique dating for such a short section of ring pattern. *It doesn’t matter how good the match is*. … anyone trying to tell you that they have dated such a short sample is kidding both themselves and you.

He adds that there is nothing unique about this example. Pilcher [1990] says similarly:

> There are … examples in the literature of [tree-ring matching] on timbers of less than 50 years…. Most of these must be treated with considerable caution. … the dating is not true dendrochronology but is tree-ring-assisted dating or even tree-ring-assisted guesswork.

Furthermore, Pilcher & Baillie [1987] tested sequences of rings from living (Irish oak) trees against a nearby master dendrochronology. For ring sequences of less than

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[5] For a discussion of problems in using archaeology to narrow the window of dates within which to search for a tree-ring match, see Baillie [1995: ch.3]. Some remarks related to this are also given in Section 7.

80 years, half of the sequences gave no statistical indication at all for the correct date. In other words, trees with less than 80 rings would, in general, not be reliably datable.

The Anatolian investigators themselves say that at least 100 rings are typically needed to be certain of a match of a tree against the master dendrochronology.

In eastern Anatolia is the archaeological site of Tılle Höyük (37.8 °N, 38.9 °E). This site contains the charcoalized remains of a gateway from the Bronze Age (see Figure 2). The gateway was constructed from many trees. Of those trees, 26 were matched against each other to form a master dendrochronology for the site [Kuniholm et al., 1993]. The gateway master does not extend from the present (it is only 218 years long), but was dated by other means (see below). Since the date for the gateway was announced, in 1993, it has been much cited by the investigators. In 2005, the investigators confirmed their confidence in it [Kuniholm et al., 2005].

Among the 26 trees in the gateway master, 6 had fewer than 40 rings recovered. Moreover, 21 of the trees had fewer than 60 rings recovered. Only two trees had more than 100 rings recovered, and their overlap (according to the investigators) comprised only 33 rings. The tree-ring matches used for the construction of the gateway master are thus seriously unreliable—so much so that the master could be said to not exist.

Even if the gateway master had been well constructed, it would still then need to be dated (because it does not extend from the present). The date for the gateway master was obtained by matching it against the Gordion master, and the principal investigator claimed that the resulting match was "excellent" [Kuniholm, 1991]. The matching, though, was done primarily on the basis of D-scores [Kuniholm et al., 1993]. As discussed in Section 2, D-scores make a somewhat-arbitrary choice. Moreover, if t-scores had been used instead, the date would have been over 150 years later (the match claimed by the investigators had a t-score of 4.5, but there was another match that had a t-score of 5.1 [Kuniholm et al., 1993: p.189]).

The match against the Gordion master was additionally asserted to have been "checked visually by sliding the graphs against each other" [Kuniholm et al., 1993: p.189]. The relevant graphs are shown in Figure 5. The gateway master [Kuniholm et al., 1993: fig.75] is on the top and the Gordion master [Kuniholm, 1993: insert] is in the middle. The alignment of the two graphs shows the investigators' claimed match. The bottom graph is purely random; it is shown for comparison purposes. The visual match of the top and middle graphs seems to be far from convincing.

Finally, the wood from Tılle Höyük might be undatable even in principle. In order to match trees against the Gordion master dendrochronology, there must be substantial correlation between the climate of the site where the trees grew and the climate of Gordion. Of the various aspects of climate that affect tree growth, (growing-season) precipitation is arguably the most important (with temperature and perhaps cloud cover also being highly consequential). Yet only about 12% of the variation in precipitation at Tılle Höyük is shared with the variation in precipitation at Gordion, at least in modern times.[6] (Ancient times would seem unlikely to have been greatly different, although that cannot be ruled out.) This seems likely too small to be confident of a reliable match for Tılle Höyük (given the number of years for which rings are available). Thus, even if the gateway master had been reliably constructed, it might not have been datable against the Gordion master. More general aspects of comparing tree rings from different sites are considered in the next sections.

[6] This is based on data for 1901–1998 [CRU, 2003]. Statistical analysis is by the author, for both annual and growing-season (considered here as April–September) precipitation.

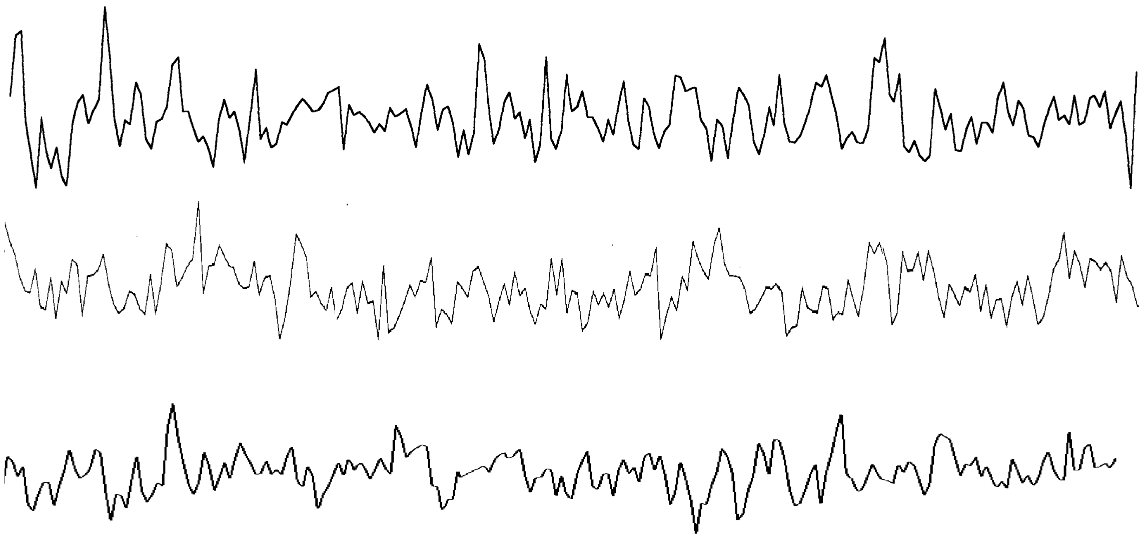


Figure 5. The gateway master, the Gordion master, and a random graph. (The random graph was generated with a moving average process (of order 1) that had the same autocorrelation as the gateway data. High variation at the ends of the gateway graph might be due to the small sample sizes there.)

5. Testing *t*-scores

This section presents some analyses for tree rings from modern trees. Modern trees can be analysed more readily that ancient trees, because much data for modern trees has been published in the International Tree-Ring Data Bank.[7] By analysing modern trees, some of the potential problems with ancient trees will become clearer.

As mentioned earlier, for Anatolian archaeological work, tree-ring matches are often made solely on the basis of ring-width measurements (not visually comparing whole wood). In this section, then, I consider the *t*-scores for the tree comparisons. One of the purposes of this section is to determine how high a *t*-score is needed in order to have a reliable tree-ring match. As discussed in Section 2, most tree-ring specialists will tend to consider a *t*-score greater than 3.5 as indicating a valid match, and a *t*-score above 5.0 will almost always be considered as being from a certainly-valid match. (The number of tree rings being compared is also relevant: 100 rings is generally considered to be enough for matching.)

In the following, all *t*-scores were calculated after applying the transformation of Baillie & Pilcher [1973] to the (standardised) ring widths (the transformation is to replace ring width w_i by $\log(5w_i/(w_{i-2}+w_{i-1}+w_i+w_{i+1}+w_{i+2}))$). This seems to be the calculation that has been used for Anatolian tree-ring studies.[8] (For comments related to this calculation, see Cook et al. [1990: sect.3.3]. I also tried some other calculations; the qualitative conclusions were similar to those reached herein.)

As a first example, I examine trees rings from a site in south-western Turkey (36.7 °N, 29.9 °E, 1800 m above sea level).[9] The master dendrochronology for the site

[7] For details regarding the International Tree-Ring Data Bank (ITRDB), see http://www.ngdc.noaa.gov/paleo/treering.html and Grissino-Mayer & Fritts [1997].

[8] See the documentation for the Cornell tree-ring analysis program, available at http://corina.sourceforge.net/api/corina/cross/TScore.html (accessed 2005-06-14).

[9] ITRDB file turk006.crn.

spans AD 1360–1988. The trees are junipers (the same species as the master dendrochronology for Gordion from ancient times). Consider the century-long portion spanning 1533–1632. If trees (from the site master) spanning 1533–1632 are compared with the site master at 1651–1750, the *t*-score is very high: 5.9. That is, if the trees rings from 1533–1632 had been found without any context, and if the master had only spanned, say, AD 1600–1988, then the tree rings would almost certainly have been claimed to date to 1651–1750. Indeed, the *t*-score of 5.9 is so high that almost all tree-ring specialists would accept the match; yet the date would be incorrect.

Figure 6a shows the highest *t*-score of an incorrect match for each century-long portion of the master dendrochronology. For example, the figure shows that for the century-long portion beginning at 1533, there is an incorrect match with a *t*-score of 5.9. (The figure does not indicate the position of the incorrect match, merely what the *t*-score of the worst incorrect match is.)

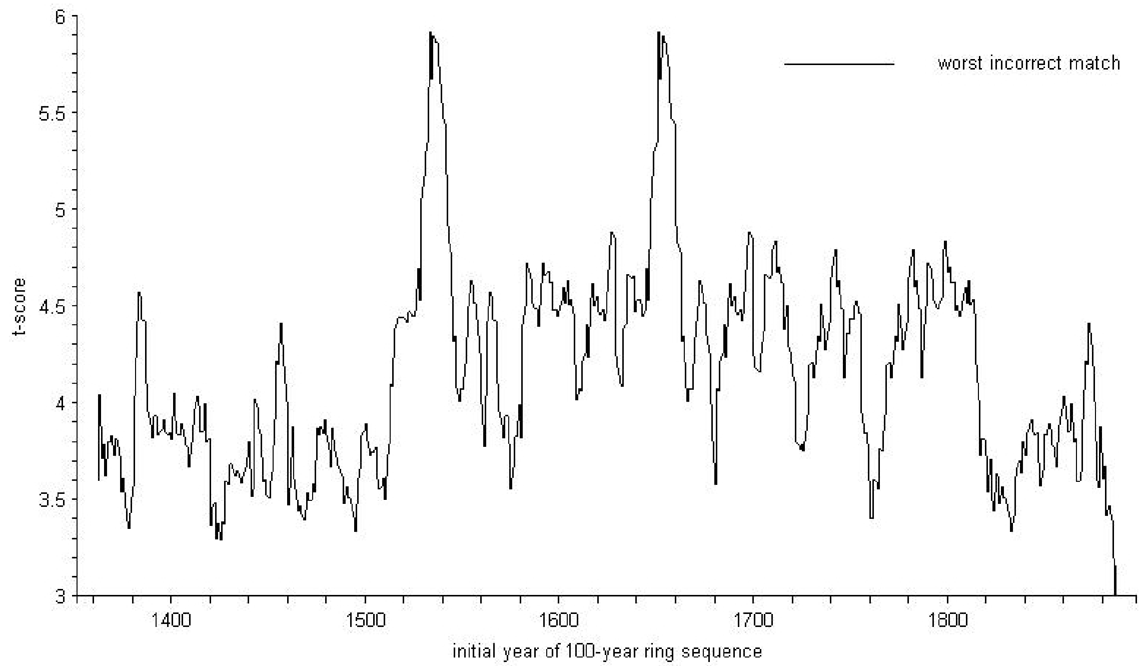
The figure demonstrates that a match with a *t*-score below 5.0 has a substantial chance of being erroneous (and a *t*-score of at least 6.0 seems to be necessary to have a truly secure match). If Anatolian tree-ring studies only accepted matches with *t*-scores well above 5.0, most of the presently-claimed matches would have to be rejected.

For the second example, I examine trees rings from a site in north-western Turkey (40.0 °N, 30.1 °E, 1400 m above sea level),[10] about 85 km north-west of Gordion. The master dendrochronology for the site spans AD 1306–1980. The trees are pines (which are coniferous, like junipers). Figure 6b is analogous to 6a, for trees at this site. As shown, the risk of an incorrect match is only slightly less than the risk for the junipers at the site in the first example.

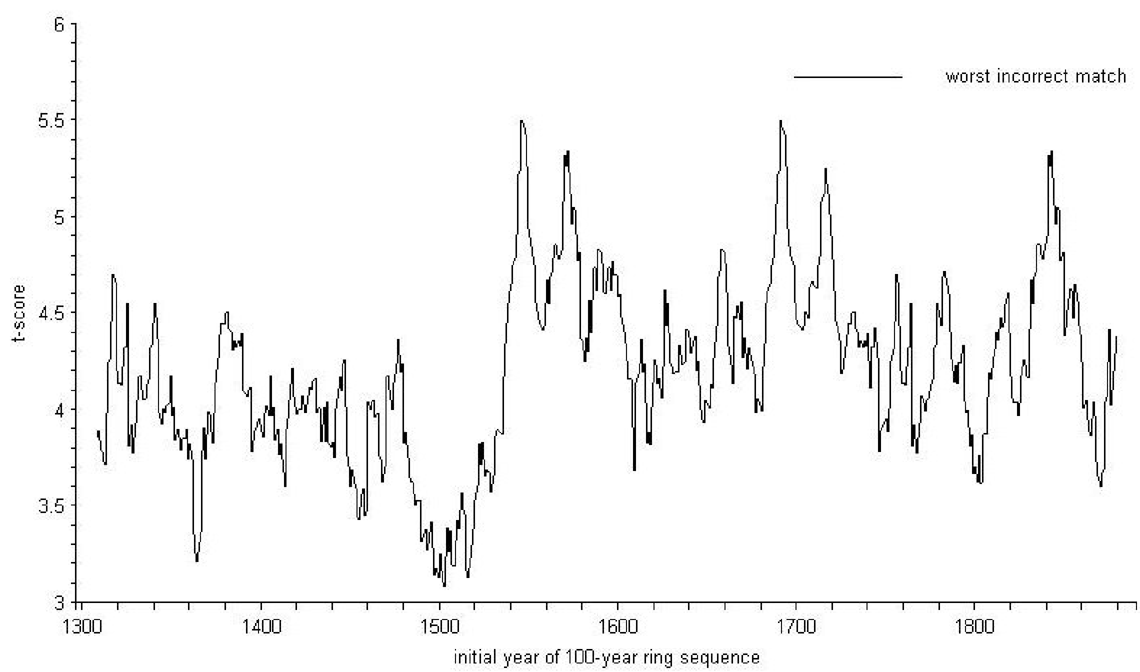
These two examples actually underestimate the problem, because each compares a century-long portion of the master against the master, rather than a single tree against the master. Comparison of a single tree against the master would naturally tend to be less reliable (as mentioned in Section 2). Additionally, the master dendrochronologies are less than a millennium long: the longer the master, the greater the chance of an incorrect match. (The two sites examined here have the longest masters among those Anatolian sites for which (i) there is data in the International Tree-Ring Data Bank and (ii) P.I. Kuniholm is a (co-)contributor.)

In both the above examples, the trees being matched against the master were of the same species and grown at the same site as the master. This is what is done when constructing a master dendrochronology for a site. The examples used century-long portions of ring widths; a century was used because the Anatolian investigators have claimed that they can generally date a tree with 100 rings. That claim is contradicted by the above: a tree with 100 rings can be reliably dated only if its *t*-score (against the master) is well above 5.0. Moreover, even if the examples had used portions that were 250 years long, incorrect matches with *t*-scores of 5.0 would still have occurred (figures not shown). Plainly, then, the master dendrochronologies for ancient Anatolia are not reliable. (The master dendrochronologies of the modern sites probably are reliable, or nearly so, because many of the trees that were used to construct them were living; so the dates of those trees were known with certainty.)

[10] ITRDB file turk001.crn. This site is in Eskişehir, and it is also discussed in Section 7.



(a)



(b)

Figure 6. The *t*-scores of some incorrect matches (at two different sites). (In principle, a tree-ring date should be exact. Herein, however, a date is considered to be incorrect only if it is at least five years from the correct date; this is conservative (and also treats autocorrelation).)

6. General aspects

The shipwreck and the gateway are from two of many archaeological sites that are claimed to have been dated in Anatolian tree-ring studies. How bad are the others? The others have not been published in sufficient detail to be sure; indeed most have not been published at all—the dates have simply been announced. That is, the shipwreck and the gateway were not chosen because they are especially strong examples of bad practice, but because they are the two sites that have been published in greatest detail. There is only one other site that has been published in some detail (Kaman-Kalehöyük [Newton & Kuniholm, 2001; Newton, 2004: app.3]).[11] The master dendrochronology for that site may be mostly reliable (though see Section 8), but no information at all has been published on how this matched against the Gordion master.

To summarise, there are three serious problems in Anatolian tree-ring studies.

1. The statistics that are used can too-readily give incorrect matches.
2. Wood is matched with too few overlapping rings to give reliability.
3. The visual analysis claimed to resolve the above problems is illusory.

These problems interact with, and are exacerbated by, the following.

4. Wood was reused by ancient peoples, across centuries and even millennia.
5. Very different species of trees have sometimes been employed.
6. Anatolia has different climatic regimes, sometimes only weakly related.

The remainder of this section has some brief remarks about each of those six issues. (An additional problem, not considered here, is how to deal with missing rings. In Anatolia, junipers (the most important species used in Anatolian tree-ring work) will, in some years, not grow a ring: Newton [2004] gives examples. Such missing rings could cause statistical matching to mislead; as such, the problem is potentially serious.)

(1.) The statistical approach used for Anatolia was discussed at length above.

(2.) Some discussion of matching short sequences of rings was given in Section 4. The number of rings needed to get a reliable match is dependent on the similarity of the climates at the sites where the trees were grown. There is no fixed minimum number of rings needed: very occasionally distinctive patterns of rings will occur within, say, 80 years, but usually they will not. (As well, extra information can be gleaned from examining how individual rings formed—e.g. if earlywood has high density or latewood is wide—and this can aid matching. Such extra examinations, though, are seldom performed in Anatolia.) For further discussion, see Section 5.

(3.) It is important that all data be visually examined. Given the priority of visual analysis in tree-ring matching, though, there should be some check on the skill of the investigator. Such a check is easy to make: blind tests, where wood samples are chosen at random (perhaps from among those whose match against the master have the lowest *t*-scores) and the investigator is asked which among suggested matches are valid/invalid. For Anatolia, no such tests have been reported.

(4.) During ancient times, wood was often reused. For example, an investigation of the remains of a Middle Bronze Age building, which comprised 26 timbers, concluded that all the timbers had been reused from some Early Bronze Age structure—dated several centuries earlier [Kuniholm, 1994]. In fact, similar reuse of wood still occurs in modern times: for example, the investigators have concluded that the joist in a

[11] Detailed information has also been published for the site of Kültepe [Kuniholm & Newton, 1989; Newton, 2004: app.2]. The investigators, however, no longer claim to have a date for this site that is near reliable; for example, Newton & Kuniholm [2004] say that the date "should be thought of as tentative, subject to … modification"—indeed, their *t*-score is only 4.1. (The tentative match is actually just the best that could be found within the date range allowed by radiocarbon ages: this is not a valid basis for dating, as discussed in Section 8; furthermore, the radiocarbon ages are internally inconsistent and are unlikely to have the accuracy assumed.)

modern Turkish house is over 6000 years old [Kuniholm, 2001]. Thus, when a tree is recovered from an archaeological site, it cannot be known a priori in which millennium the tree grew. This plainly increases the chance of a false-positive tree-ring match. (The principal investigator has stated that he has no doubt that some of the trees used to construct the gateway came from earlier times (P.I. Kuniholm, e-mail to the author, 2002-06-03). The investigator claims, though, that the trees used for the site dendrochronology were all from the time of the gateway's construction: no evidence for this claim has been adduced.)

(5.) Matching trees of different species is naturally more error prone than matching trees of the same species. The Gordion master dendrochronology is composed of juniper. Trees of other species, though, have been matched against this. For examples, the shipwreck wood is cedar and the gateway wood is oak. Some work has been done with modern trees to gain some understanding of the issue [Kuniholm, 1996; Newton, 2004: ch.2]. This work, though, focussed on wood with over 500 rings: so many rings makes matching much easier, but it is unrealistic in most archaeological contexts. A good understanding of the issue would require much more work (also to understand how different species react under differing environmental conditions).

(6.) Tree-ring matching requires that the trees being matched grew in areas that have correlated climates. Anatolia, though, has different climatic regimes [Taha et al., 1981], and (growing-season) precipitation in some regions is largely uncorrelated with precipitation in other regions. Hence trees from some regions will likely tend to be largely unmatchable against others. (The shipwreck wood might even be from Syria–Lebanon,[12] whose precipitation has very little correlation with that of Gordion.[13])

Even within a very small area, local effects can sometimes lead to large differences in tree-ring growth. For example, LaMarche [1974] measured living trees at two sites in Nevada that were on the same side of a mountain, with one site just 130 m higher than the other, near the tree line: the ring widths of trees from the two sites showed no general correlation. As another example, Hillam [1980] compared master dendrochronologies from two sites at York, England, with a master dendrochronology from Exeter, also in England: the first York site compared with Exeter gave a t-score of only 0.5, and yet the second York site compared with Exeter gave a t-score of 3.5. (In modern times, York and Exeter share about 50% of their variation in precipitation.[14] It should be noted though that these English master dendrochronologies included few trees, which weakens matching.) Local effects might be particularly relevant in Anatolia, because it has a highly-variable topography, with mountains.

A further complication is that climatic conditions change over time. For example, master dendrochronologies from Scotland and Northern Ireland match extremely well during 1800–1899 (t-score of 11.4), but much less well during 1700–1799 (t-score of 4.3) [Baillie, 1982: p.109]. (Recall from Section 2 that a t-score of 4.3 is generally interpreted as indicating a valid match, though Section 5 presents evidence that higher t-scores are required.) Similarly, master dendrochronologies for Exeter and Nantwich (both in England, about 275 km apart) match fairly well during AD 1061–1216 (t-score

[12] This follows from considering both the archaeology of the ship [Pulak, 1997] and the areas where cedar grows (in modern times)—Cyprus, southern coastal Turkey, and Syria–Lebanon.
[13] The correlation in precipitation was calculated from data for 1901–1998 [CRU, 2003], with statistical analysis by the author. Ancient times would seem unlikely to have been materially different, because Syria–Lebanon is downwind from the Mediterranean, whereas Gordion is largely downwind from the Black Sea.
[14] This is based on data for 1901–1998 [CRU, 2003]. Statistical analysis is by the author, for both annual and growing-season (considered here as April–September) precipitation.

of 4.55), but not really at all during AD 930–1060 (*t*-score of 0.85) [Hillam, 1980]. This second example, in particular, illustrates the danger that a changing climate can pose for tree-ring matching. And, for Anatolia, the climate is known to have changed markedly over the millennia [Bottema, 1997; Roberts et al., 1999; Roberts et al., 2001]. Indeed, remains of old trees have been found at locations where no trees could possibly grow today [Kuniholm, 2001; Kuniholm & Newton, 2001].

So, consider a tree that has been recovered from an Anatolian archaeological site: in general, we do not know the millennium in which it grew, or the location in which it grew, and we have a poor understanding of the climatic conditions in which it grew. All of this makes a firm ground for extra conservatism when matching Anatolian tree rings.

Lastly, it should be noted what happens if trees are erroneously matched against a master dendrochronology and then included as part of that master. This error will lead to corruption of the average ring widths of the master. (And that could then lead to the incorrect inclusion of other trees in the master.) The Gordion master dendrochronology contains some logs that have over 500 rings, with several centuries of overlap; the matching of logs with so much overlap, all of the same species and likely grown near the Gordion site, is almost certainly valid. This does not mean, however, that all trees in the Gordion master are correctly dated; i.e. the average ring widths of the master—that is, the master dendrochronology itself—could still be unreliable. If the master is unreliable, then plainly the match of other trees against it would tend to be less reliable.

7. Case: Assiros, Greece

The Anatolian investigators have claimed that wood from Greece can be matched against wood from Anatolia. In particular, they have claimed that much ancient Greek wood can be matched against the master dendrochronology from Gordion. This section considers one example of that claim, the only example to have been reported with any details: wood from Assiros (40.8 °N, 23.0 °E), in north-eastern Greece (see Figure 2).

The wood from Assiros comprises four oak timbers, all charcoalized, which were matched to form a master dendrochronology for the site. This Assiros master is 104 years long, and Newton et al. [2003] match it against Gordion with a *t*-score of 4.46. From Section 5, then, it might be concluded that the match is insecure. Newton et al., however, have some additional evidence for the match. This evidence is radiocarbon ages for two of the timbers (which give approximate dates). The claimed match is the only match with a reasonably-high *t*-score that is consistent with the radiocarbon ages.

There are serious problems with the radiocarbon dates. (In particular, neither the calibration curve nor the calibration algorithm have the accuracy assumed. As well, regional variation was ignored: for related comments on this, see Keenan [2004] and Keenan [2002].) Here though, I consider only the dendrochronology, and assume that the radiocarbon dates are roughly correct.

Before considering the ancient wood, I first examine modern wood from two sites: in Chalkidiki, Greece (40.5 °N, 23.6 °E, 600 m above sea level)[15] and Eskişehir, Turkey (the site of the second example in Section 5). The Chalkidiki site is about 60 km south-east of Assiros; the Eskişehir site is about 85 km north-west of Gordion. (The two modern sites are marked by crosses in Figure 2.) The Chalkidiki wood is oak, the same as Assiros; the Eskişehir wood is pine, which is similar to the juniper of the Gordion master. (For some discussion of how similar the widths of juniper rings are to the widths of pine rings (grown within the same region), see Newton [2004: ch.2].) The

[15] ITRDB file gree006.crn.

locations of Chalkidiki and Eskişehir, and the wood species, thus suggest that cross-matching (of tree rings) between these two sites should be roughly as good as cross-matching between Assiros and Gordion.

In Figure 7, the thick line shows the *t*-score of each century-long portion of wood from Chalkidiki against the same century of wood from Eskişehir. As an example, consider the Chalkidiki tree rings from 1835–1934: the figure shows that when those rings are matched with Eskişehir tree rings from the same years, the *t*-score is only 1.6. Figure 7 (thick line) shows that all matches have *t*-scores less than 3.5. But then why did Newton et al. [2003: p.181] find a *t*-score of 4.46 when comparing trees from Assiros and Gordion? The answer is given in Section 5: we should expect that there will be *incorrect* matches with *t*-scores as high as 4.46, just due to chance. This is confirmed by the thin line in Figure 7, which shows the highest *t*-score of incorrect matches between Chalkidiki and Eskişehir. For example, the Chalkidiki tree rings from 1835–1934 have an incorrect match against Eskişehir with a *t*-score of 4.1; the position of the incorrect match is not shown: in this example, it is 1854–1953.

If the highest *t*-score of a correct match is less than 3.5 and there are incorrect matches with *t*-scores greater than 3.5, how can unknown trees from Chalkidiki be dated against trees from Eskişehir? They plainly cannot be dated via *t*-scores. Moreover, this is true even if the potential range of dates is narrowed via radiocarbon. In the example of Chalkidiki wood from 1835–1934, we saw that there is an incorrect match at 1854–1953 with a *t*-score of 4.1: this incorrect match is 19 years from the correct match. The radiocarbon dates could not realistically catch errors of only 19 years. (Moreover, errors even smaller than 19 years could occur almost as readily.) Hence the *t*-scores have no value at all for determining the date of the Chalkidiki wood. And the same conclusion almost certainly holds for dating Assiros wood against trees from Gordion.

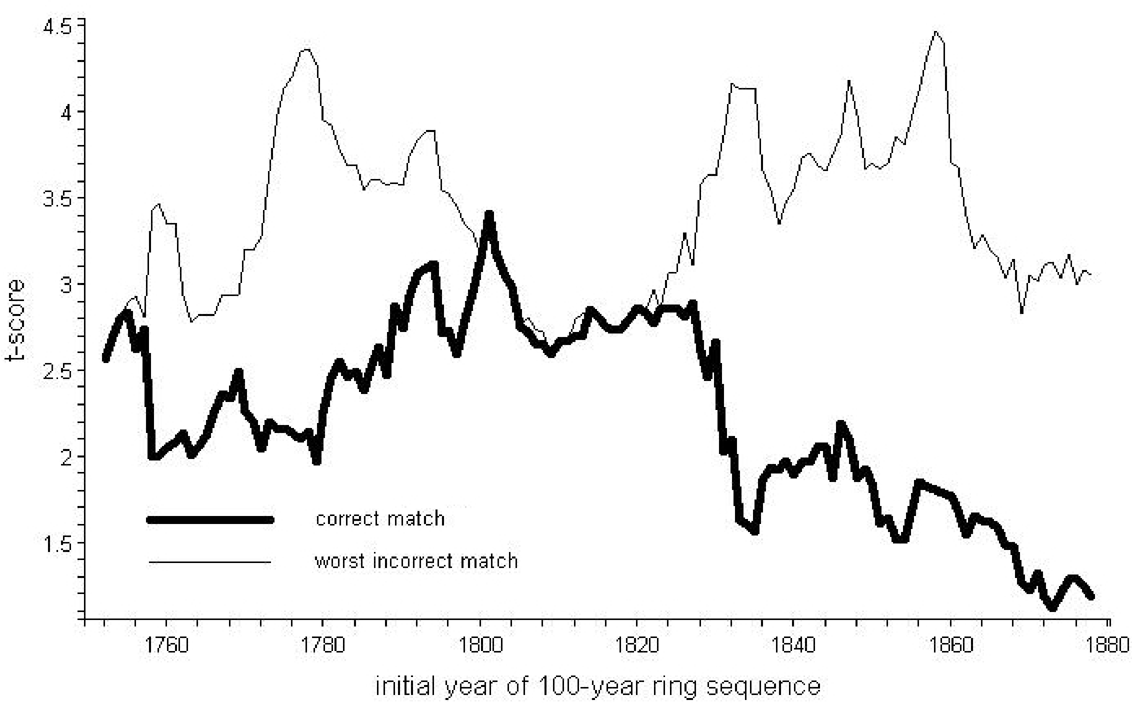


Figure 7. Infeasibility of matching wood from Chalkidiki against wood from Eskişehir. (The Eskişehir rings that are considered here are those from years 1750–1979; these are the same years for which replicated rings from Chalkidiki are available. As in Section 5, a date is conservatively considered to be incorrect only if it is at least five years from the correct date.)

It is also interesting to compare the graphs of the Assiros and Gordion tree-ring widths. The graph for Assiros displays one large peak and one large dip [Newton et al., 2003: fig.6]: neither of these events is in the Gordion graph (using the claimed match). The conclusion from this and the above discussion of *t*-scores is that the Assiros trees have not been, and likely cannot be, even plausibly matched against the Gordion master.

The Assiros wood also demonstrates how the use of radiocarbon involved a logical fallacy. If a tree-ring match is the best match within the date range that is allowed by radiocarbon, this does *not* imply that the match is correct. Rather, an unreliable tree-ring match should always be regarded as unreliable. In such cases, the tree-rings provide little information about the true date. (The same conclusion holds if instead of radiocarbon, some other dating constraint is applied, e.g. archaeology.)

It is natural to ask why the Assiros wood cannot be matched against Gordion wood. The likely answer is that Assiros and Gordion lie in distinct meteorological regimes. At Assiros, the prevailing winds are from the north-west: Assiros lies in the Mediterranean meteorological regime [Reddaway & Bigg, 1996; Barry & Chorley, 2003: fig.10.26; Keenan, 2002: fig.1]. At Gordion, by contrast, the prevailing winds are from the north-east, from across the Black Sea [Reddaway & Bigg, 1996; Barry & Chorley, 2003: fig.10.26; Keenan, 2002: fig.1]. Thus, a priori, we should not expect that wood from Assiros could be matched against wood from Gordion. There is a small correlation between the precipitations at the two sites—in modern times, the two sites share about 5% of their variation in precipitation (likely due to storms moving northward through the Aegean [Barry & Chorley, 2003: fig.10.27]); additionally, about 20% of the variation in temperature is shared.[16] It might be, then, that with over, say, 500 tree rings, matching is possible. As demonstrated, though, 100 rings is not enough.

(Newton [2004: ch.2] claims that trees in Greece can be matched against trees from Anatolia: her analysis used more than 500 rings. Moreover, the locations of the sites used for the analysis are not stated. Trees from opposite sides of the southern Aegean would be expected to cross-match more strongly than trees from Gordion and Assiros, due to having partially-shared meteorologies. Indeed, a figure similar to Figure 7 that compares trees from a site in south-western Anatolia (37.2 °N, 28.4 °E, 1200 m asl) and from a site in southern mainland Greece (36.9 °N, 22.3 °E, 1400 m asl) indicates that reliable cross-matching between these sites can be done with 250 rings (figure not shown).[17])

8. Discussion

The central conclusion is clear: Anatolian tree-ring studies are very untrustworthy and the problems with the work should be plain to anyone who has familiarity with the field. This is a serious matter. Consider that the work has been published in respected research journals and been ongoing for many years. How could this have happened?

In almost all branches of science there is a check on the validity of published work: other researchers can, and often will, independently seek to replicate the research. For example, if a scientist does an experiment in a laboratory, comes to some interesting conclusion, and publishes this, then another scientist will replicate the experiment, in another laboratory, and if the conclusion is not the same, there will be some

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[16] Statistical analyses are by the author, based on growing-season data for 1901–1998 from CRU [2003].

[17] The ITRDB files for the two sites are turk011.crn and gree009.crn.

investigation. This check much helps to insure the integrity of the system. Tree-ring studies, though, do not have this check, because the wood that forms the basis of a tree-ring study is irreplaceable: no other researchers can gather that wood.

Additionally, tree-ring investigators typically publish little more than conclusions (occasionally with average ring widths for a master dendrochronology). This is true everywhere, not just for Anatolia. Moreover, there is little competition among tree-ring investigators, in part because investigators for one region typically do not have access to data for other regions. The result is *a system in which investigators can claim any plausible results and are accountable to no one*.

Archaeologists should not submit to this system. There might be temptation to accept a tree-ring date without supporting measurements, particularly when the date agrees with the archaeologists' hypotheses. To accept such a date, however, implies acquiescence to a system that does not have sufficient checks to insure its integrity. Moreover, a solution for the problem is clear: ring measurements from each tree should be published, to make them available for independent scrutiny. A data depository is already established: the International Tree-Ring Data Bank. And as Kuniholm [2002: p.67] has stated, regarding tree-ring data, "keep in mind that unpublished information is next to worthless".

Appendix: Response to a critique

In 2002, I published a paper that included a brief critique of Anatolian tree-ring studies [Keenan, 2002: Excursus]. (The critique concluded that "Anatolian [tree-ring studies] should be regarded as suspect and in need of independent scrutiny".) A response to the critique was later published by investigators involved with Anatolian tree-ring studies [Manning et al., 2002: p.747–750].[18] This section discusses that response. In what follows, "ADP" is the acronym for *Aegean Dendrochronology Project*, the project under which the Anatolian tree-ring work has been conducted.

First, consider the following quote from the response.

> All crossdating [done in the ADP] employs established dendrochronological techniques (Cook and Kairiukstis 1990); the ADP in published reports has followed the European standards established by the laboratories in Belfast, Birmensdorf, and Hamburg.

The cited reference, Cook & Kairiukstis [1990], makes no mention of *D*-scores. Belfast has not used *D*-scores (or *g*-scores: see discussion in Section 2). Birmensdorf has not used *D*-scores (F.H. Schweingruber (Birmensdorf), private communication, September 2003). Hamburg has relied primarily on *t*-scores with visual matching, and a minor use of *g*-scores only (P. Klein (Hamburg), private communication, September 2003). Moreover, none of the three laboratories would rely solely on visual matching: all require statistical support for a match—unlike what was done with the shipwreck.

Cook & Kairiukstis [1990] are the source of the quote characterising the use of trees with less than 50 rings as tree-ring-assisted guesswork (see Section 4). The quote is actually due to J.R. Pilcher, one of the two lead tree-ring investigators at Belfast. The other lead Belfast investigator is M.G.L. Baillie, who is quoted saying that anyone who claims that they can date short sequences of rings is kidding both themselves and you.

In other words, the primary quantitative method used for Anatolia is not supported by the sources cited in the above quote, and the use of short overlaps in ring matching is

[18] This response was published in July 2003, notwithstanding the nominal date.

strongly contradicted by them. Contrary to the quote, all published Anatolian reports of which I am aware cite *D*-scores or short sequences of rings or both:

- for the gateway, *D*-scores were the primary means for choosing the date, and short pieces of wood were used (see Section 4);
- for the shipwreck, *D*-scores were mentioned (but no quantitative methods were relied upon) and the two pieces of wood overlapped with only 23 rings;
- the two other reports on Anatolian tree-ring archaeology of which I am aware that make mention of matching methods also cite *D*-scores and claim that they are one of the three "standard" tests (along with *t*- and *g*- scores, which make up *D*-scores) [Kuniholm & Newton, 1989: p.291; Kuniholm et al., 1992: n.3];
- a summary table of matches for modern trees also cites *D*-scores [Kuniholm, 1996]; and
- reports on the archaeological site of Kaman-Kalehöyük claims to date wood with less than 60 rings [Newton & Kuniholm, 2001; Newton, 2004: app.3].

Furthermore, the principal investigator in Anatolian tree-ring studies stated in 2002 that *D*-scores continued to be used in much the same way as they had for the gateway dating (P.I. Kuniholm, e-mail to the author, 2002-06-03). (Section 6 points 5 (different species) and 6 (different climates) are also relevant, but not reiterated here.)

Another quote from the response is this.

> The core chronology comprises juniper (contra [Keenan's] assertion that different species are mixed)….

The core (i.e. Gordion) master dendrochronology does indeed comprise only juniper. Very different species of trees, however, have been matched against it—e.g. the gateway and the Kaman-Kalehöyük wood, both of which are oak. Here is what the critique said: "Anatolian dendrochronological work (such as the gateway matching) has been done using a mixture of deciduous and coniferous trees". (Oak is deciduous; juniper is coniferous.) Thus, the critique's claim is valid.

Below is another quote from the response to the critique, discussing the gateway.

> Keenan does not name the site—it is Tille Höyük—and he merely repeats the previous misinformed claims by Porter…. Keenan fails to display a reading of the text by Kuniholm et al. (1993), where they explain what the samples comprise, and other factors apart from simple statistics … that were taken into account….

What are the criticisms being made here? (i) It is true that the critique did not name the archaeological site at which the gateway was found; how important is this? (ii) Only a minority of the problems discussed in the critique were previously discussed by R.M. Porter (whose work was duly credited). (iii) The samples comprise the remains of trees, as always (strictly, they were charcoal, which if anything makes the tree-ring matching less reliable). (iv) The only factor apart from statistics that was taken into account was the visual check discussed above (in Section 4), at least according to Kuniholm et al. [1993]; indeed, there could be little else, because the wood had been charcoalized.

The response additionally states the following.

> Keenan purports to throw considerable doubt on the validity of 30 yr of ADP work … through reference to the dating of 1 case—a "gateway."

The critique did indeed only present the case of the gateway. Herein is also presented the shipwreck. Those are the two Anatolian tree-ring studies that have been published in most detail. Those two cases seem to be representative of Anatolian practice (the investigators have not disputed this). Yet if proper practice had been employed, neither the gateway nor the shipwreck would have been dated. I believe that this should indeed throw considerable doubt on much of the work done in Anatolian tree-ring studies. (Also, such doubt is strengthened by the issues for modern trees discussed in Section 5.)

As well as the above quotes, the response to the critique had one other statement of significance.

> "Keenan devotes much of his "excursus on dendrochronology" [i.e. the critique] to a critique of the exploratory D-value …, he mischaracterizes any use of this value in determining accepted crossdates."

The critique only discussed *D*-scores in one paragraph. Here is what was said: "There are also additional problems with Anatolian [tree-ring] work, which will not be detailed here (e.g. the use of D-scores, which are meaningless …)". Thus the quoted statement is untrue. Additionally, the claim that *D*-scores are "exploratory" is contradicted by several publications in Anatolian tree-ring studies (cited above) that rely on *D*-scores.[19]

In summary, the response to technical criticisms is comprised of misleading and invalid statements.

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[19] After the publication of the response, one of the co-authors acknowledged that *D*-scores are "not subject to the rules of statistical probabilities" [Newton, 2004: ch.2].

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