Tree-Rings, Kings, and Old World Archaeology and Environment:

Papers Presented in Honor of Peter Ian Kuniholm

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Contents

Cold Fusion: The Uneasy Alliance of History and Science

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Abstract: *The goal of establishing a secure second millennium* BC *absolute chronology linking Egypt, the Near East, Cyprus and the Aegean world is as elusive as it is important. Communication between scholars of ancient texts and archaeologists, on the one hand, and physical scientists, on the other, is often marked by lack of understanding of the nature and degree of uncertainty in data from other disciplines. This paper examines the reliability of data from the fields of Egyptian and Near Eastern texts and archaeology, Egyptian astronomical dating, and interconnections between Egypt, Cyprus, and the Aegean during the 16th and early 15th centuries* BC*, in comparison with ice-core, tree-ring, and, in particular, radiocarbon dating.*

Fifty years ago C. P. Snow, the distinguished British scientist, novelist, and senior civil servant, wrote an article and delivered a BBC lecture on "the two cultures" (1959). Snow described Science and the Humanities as living in mutual ignorance and disdain. Scientists, said Snow, generally regarded humanistic research as trivial and akin to postage-stamp collecting, while most humanists, who would be ashamed to be found ignorant of one of the lesser sonnets of Shakespeare, could profess unashamedly their ignorance of the Second Law of Thermodynamics.

Unfortunately, the problem of mutual incomprehension identified by Lord Snow seriously affects chronological studies today. I can count on the fingers of one hand the number of historians and archaeologists who have made a serious attempt to visit the appropriate laboratories and become familiar with the potential contribution and accompanying uncertainties of the relevant sciences—glaciology, dendrochronology, radiocarbon dating, astronomy (Egyptian and Babylonian)—or to grasp the essence and understand the uncertainties of Bayesian statistics as applied to radiocarbon dates. Conversely, I know of no physical scientist who has even attempted to master the essentials of Egyptian-based textual plus astronomical dating and its Near Eastern correlates or the archaeologically established interconnections with the Aegean. I have heard one distinguished physical scientist state at a conference that chronological evidence from the hard sciences is critical because archaeologists have no better means of dating than highly subjective judgments of the duration of pottery styles, and another scientist ask at a conference why historians believe any texts, since people always lie. Conversely, some archaeologists and art historians say that they ignore scientific analyses because scientists' assertions change so frequently. Grist for this mill was provided by erroneous initial geographic sourcings of both metals and ceramics; the inaccurate initial chronological placement of the Anatolian floating tree-ring chronology and the wood from the Uluburun shipwreck; the proposed Theran eruption date of 1628 BC, announced with great confidence, but subsequently disavowed; the claim, since disproved, of conclusive similarities in the chemical composition of glass particles in the Greenland ice core and Theran tephra, and erroneous claims based on ^{14}C. (Of course "science progresses by correcting its mistakes" [Dawkins 1998].) The problem is compounded by boundaries

It is a pleasure to offer this small tribute to Peter Kuniholm, friend and scholar. His willingness to dare, his determination, his dedication to students, his physical courage in the face of injury, and his unsurpassed work ethic have created the field of Near Eastern and Aegean dendrochronology.

I am grateful to Sturt Manning and Peter Kuniholm for advice and assistance, given wholeheartedly notwithstanding their knowledge that the views expressed would differ from, and in some cases be critical of, their own. I am grateful as well for the invaluable editorial assistance of Jayne Warner, Erin Hayes, Jason Earle, and Catriona McDonald. I also thank Manfred Bietak, Harriet Blitzer, Paolo Cherubini, Douglas Keenan, Oliver Rackham, Paula Reimer, Steven Soter, and Peter Warren for their contributions of information, corrections, and editorial suggestions.

within the two cultures. Many Aegean prehistorians, for example, know little of Egypt and the Near East, while many physical scientists know little or nothing about other scientific approaches to chronology or about the degree of reliability of various Egyptian astronomical dates. Recent and ongoing controversies regarding the validity of historical (archaeo-textual) approaches on the one hand, and scientific methods on the other, to the critical question of the chronology of the Middle and Late Bronze Age in Egypt, the Near East, and the Aegean illustrate perfectly the conflict of the two cultures.

I. The Textual, Archaeological, and Egyptian Astronomical Evidence

A. Egypt and the Near East

Egypt presents an essentially complete textual record back to the accession of Tuthmosis III between 1479 BC and 1468 BC, buttressed by three astronomical observations (Krauss 2007; Wiener 2003: 365; 2006a: 319; 2006b; 2007). Prior uncertainty concerning individual reigns in the Third Intermediate Period (c. 1100–650 BC) following the end of the New Kingdom have been largely resolved through the work of Kenneth Kitchen and others on textual evidence, and the chronology of the period is buttressed by one Egyptian astronomical observation (Wiener 2006b; Krauss 2007) and particularly the comparison of the description of the campaign of Egyptian pharaoh Shoshenq I in Israel and Judah on the walls of his temple with the biblical account of the invasion of Shishak (925–923 BC) in the fifth year of Rehoboam, whose dates can be closely estimated by counting back from the great battle of Qarqar in 853 BC during the reign of Ahab recorded in the Assyrian annals. There is not much wiggle room back to the beginning of the New Kingdom between 1539 BC and 1525 BC, and only a small amount, in all probability not more than a generation, back to an astronomical determination in the seventh year of the reign of Sesostris III (Wiener 2006b), whose date is disputed to a certain extent, but which must fall between c. 1875 and 1830 BC. A large majority of Egyptologists support the date advocated by Luft (2003: 202) of c. 1866 BC, but Krauss has argued for a date of 1831–1830 BC (Krauss 2006: 448–450). Textual and archaeological evidence, such as the work of Bennett on the prosopography of the 13th Dynasty (Bennett 2006; Wiener 2007), appears to support the Luft date of c. 1866 BC. Wells and Bennett (Wells 2002; Bennett, pers. comm. of 28 April 2007) have suggested that some of the recorded dates may constitute predictions rather than observations; if so, the highest possible date is still unlikely to be earlier than c. 1875 BC. Even the highest date is difficult to reconcile with any proposal to raise Egyptian chronology for the Second Intermediate Period by a century in order to accommodate a small number of tenuous ^{14}C determinations.

The Egyptian textual record includes not merely king lists, records of high officials, inscriptions on buildings, temple records, and records of the life spans of the sacred Apis bulls, but also private documents telling us how long individuals served under different pharaohs. An official named Ineni, for example, tells us how long he served under Amenophis I, Tuthmosis I, Tuthmosis II, and Tuthmosis III, taking us back to before 1500 BC. Recent work on earlier periods, including studies of the prosopography of the priests of El-Kab and on the Hyksos of the Second Intermediate Period, as well as 12th Dynasty texts, clarifies the period back to the 1866–1830 BC astronomical date (Shortland et al. 2005; Bennett 2006).

In the Near East, Assyrian records are continuous back to 911 BC. Before that, we have the information contained in hundreds of thousands of baked clay tablets used for record keeping. Studying these tablets, Brinkman more than 30 years ago was able to construct separate chronologies for Assyria and Babylonia—which he believed accurate, to within at most a dozen years—back to about 1425 BC. (1972). Brinkman subsequently noted that differences in calendars created a further source of uncertainty, amounting to a maximum of three years per century (comment at the 2006 Cornell Conference in honor of P. I. Kuniholm). Brinkman's original reconstruction indicated an eight-year overlap in the 12th century BC in the reigns of Ninurta-apil-Ekur in Assyria and Meli-Shipak in Babylonia (Brinkman 1972: 272–273; 1976: 31–33; 1977). In 2001, a German excavation in Assyria found a record of a letter from one of these rulers addressed to the other, thereby confirming the existence of an overlap in these reigns (Frahm 2002). Finally, the Near Eastern chronologies are linked to the Egyptian through correspondence between Near Eastern and Egyptian rulers and courts, particularly in the 14th century BC (Moran 1992).

A recent presentation of radiocarbon determinations from Tell el-Dab‘a in the Nile Delta produced dates a century too early for the historical dates of the Tuthmoside period (Kutschera and Stadler 2003; Kutschera, pers. comm. of 7 June 2005; Wiener 2006b). Tuthmoside dates, however, are connected to Amarna dates (where according to the Tell el-Dab‘a measurements historical and radiocarbon dates agree) by a secure succession of rulers within the same dynasty. The dates of the period when Egypt was ruled from the short-lived capital of Amarna are historically well anchored by the many tablets found there, recording the correspondence of the Egyptian pharaohs Amenophis III, Akhenaten, and Tutankhamen with many Anatolian and Levantine rulers whose dates are closely known, as well as by Egyptian texts. The moral of the story is not that the historical dates for the Tuthmoside era are wrong, but that some radiocarbon determinations produce accurate chronological dates, and others do not (Wiener 2006b; and see below).

B. The Aegean

Our historical chronology has taken us back securely to the beginning of the New Kingdom in Egypt, which is tied in many ways to the end of the LM IA period in the Aegean and a Theran eruption between c. 1545 and 1495 BC. In part the case rests on specific objects—for example the famous (or infamous) fragmentary Cypriote White Slip I bowl from beneath the tephra level on Thera, which in the view of most scholars could not have been made before c. 1560 BC, and was probably made significantly later. Moreover, time must be allowed for the bowl to have been brought from Cyprus to Thera, broken and repaired in antiquity, and then buried by the eruption (Merrillees 2001). We know about the chronological horizon of White Slip I because of the thousands of sherds of Cypriote pottery—including some White Slip I and its chronological predecessors, Proto White Slip and White Painted III, IV, and V—found in various contexts in Egypt (Bietak and Hein 2001) and the Near East (Bergoffen 2001; Fischer 2003: 265), and in Cyprus in contexts including Minoan LM IA pottery (Eriksson 2001: 62). Can the one Cypriote example from Thera be much earlier in time than all the other White Slip I sherds in datable contexts, which in turn fall into place in the Cypriote sequence behind Proto White Slip and its predecessors?

The argument does not rest on White Slip I pottery alone, but on a long sequence of Cypriote wares which can be found at sites on Cyprus such as Maroni (Cadogan et al. 2001: 75–88), and in very similar stratification at Tell el-Dab‘a in Egypt, at Ashkelon in Israel, and at Tell el-‘Ajjûl in Gaza (Bietak and Hölfmayer 2007). The appearance in Shaft Grave V at Mycenae, containing burials of the Late Helladic I period prior to or around the time of the eruption of Thera (Graziadio 1991: 434–436, 433 table 4; Dietz 1991: 248–249), of a calcite jar which in Egyptian typological comparanda analysis fits in the early 18th Dynasty (and at the earliest, at the end of the Hyksos period, although the parallels then are less close) further supports the historical chronology, particularly since the jar in all likelihood stopped in Crete on its journey to Mycenae and was modified by a spout in a fashion typical of Minoan adaptation of Egyptian stone vessels (Warren 2006: 307–308; Bietak and Hölfmayer 2007). A jug with a strap handle (Athens NM 592) from Shaft Grave IV of Late Helladic I date further supports this analysis (Warren 2006: 305–308).

Next, we have the sequence of Aegean bronze vessel shapes, which follow one another in Aegean archaeological strata and in their depictions on the walls of Egyptian tombs of known date (Matthäus 1995). Can each of these have been copied by Egyptian artists 50–75 years after they were superseded in the Aegean? Similarly, Egyptian imports, copies, and depictions in tombs of Minoan rhyta, with chronological changes in shape following Minoan examples (Koehl 2000; 2006: 342–345, 358) also lend support to a mature LM IA eruption date around 1525 BC, plus or minus 25 years at most. If LM IA ends before 1600 BC as proposed by Manning et al. (2006a: 569), such rhyta must survive as heirlooms in fixed chronological sequence with a delay in each case of about 75 years. The tombs of viziers in the reign of Tuthmosis III also show the arrival of other grand gifts of LM IB style. Moreover, six Aegean pots from good Egyptian contexts and three Egyptian pots from clear Aegean contexts are all consistent with conventional archaeo-textual dating (Warren 2006). At Knossos the lid of an alabaster jar was found with the cartouche of the fourth Hyksos ruler, Khyan, whose Middle Minoan III context has recently been reexamined after challenge but reaffirmed (Macdonald 2003: 40; Warren, pers. comm. of 4 February 2005). The proposed Aegean Long Chronology based on putative radiocarbon determinations would, on the other hand, require the lid to arrive much later in Cretan terms, in Late Minoan IB. While an attempt has been made to reconcile all the archaeological evidence with dates roughly a century higher, the argument strikes most mainstream Aegean archaeologists specializing in chronology as somewhat bizarre (Bietak 2003; 2004).

II. The Scientific Evidence—Ice Cores, Dendrochronology, and Radiocarbon Dates

What, then, is the putative scientific case for earlier dates, i.e., the source of the unease in the alliance of history and science? A recent article in *Science* magazine asserts that, apart from radiocarbon dating, there is evidence from ice cores and tree rings for a date 75–100 years earlier than archaeological dating for the Theran eruption (Friedrich et al. 2006a). There is in fact no such evidence.

A. Ice-Core Dating

As to ice-core dating, 1) the initial claim of a rare-earth element europium anomaly in both the Greenland ice around 1645 BC and Theran tephra (Hammer et al. 1987; Hammer et al. 2001) was withdrawn by the investigators (Hammer et al. 2003: 93); 2) subsequently it became clear that major differences in the bulk components of the Greenland ice and the Theran tephra made a common source practically impossible (Keenan 2003), and that the trace elements were not closely comparable (Pearce et al. 2004; Keenan 2003; Wiener 2007); and finally, 3) it was shown that the published chemical composition of the ice-core indication was much closer to the composition of an eruption of Aniakchak, a volcano in the Aleutian Chain which on independent evidence is believed to have erupted in the 17th century BC, than to Thera (Pearce et al. 2004). Moreover, wind patterns make it far more likely that the ejecta of an Alaskan volcano would reach Greenland than ejecta from Thera, and, in any event, there is no reason why every Northern Hemisphere eruption should leave an acid signal in every square meter of the Greenland ice (Wiener 2003; Robock 2000 and pers. comm.; Robock and Free 1995). In sum, to date there is no ice-core evidence for the Theran eruption.

B. Dendrochronology

There is at present no direct dendrochronological evidence for dating the Theran eruption either. The key sequence of logs from Porsuk near the Cilician Gates, 800km due east of Thera, shows a growth spurt of indeterminable cause around 1640 BC, an impossibly early date for the Theran eruption on archaeo-textual grounds (and significantly earlier than the date proposed by the recent radiocarbon analysis of a Theran olive branch covered in tephra discussed below). The Porsuk tree-ring sequence largely ends in 1573 BC, and hence is not relevant to the discussion of a later, more historically appropriate, date for the eruption. Apparent correlations of ice-core and tree-ring events in the same year or two at various places occur at several dates, including 1571–1570 BC and 1525–1524 BC (Wiener 2006a: 320–323; see also Salzer and Hughes 2007, which refers to an event so far observed only in trees in Arizona, California, and Nevada in 1544 BC), but the locations of the putative eruptions responsible for the suspected climate-forcing events are presently unknown. Examination of the chemical composition of the Greenland ice-core laminations corresponding to the small acid spikes of those years may be appropriate, if possible. The Cornell Tree-Ring Laboratory has begun efforts to source minute particles in tree rings. Perhaps one day we may have good evidence from ice-core analysis or dendrochronology.

C. Radiocarbon Dating

Arguments based on radiocarbon dating today form the principal challenge to the chronology based on texts, archaeological interconnections, and Egyptian astronomy for the beginning of the Aegean Late Bronze Age and the Theran eruption. Dates for the eruption older by 90 to 120 years than conventional dating have been proposed by some specialists in radiocarbon dating (Hammer et al. 2003: 87; Manning 1999: 335; Friedrich et al. 2006a). The years 1645 BC ±4, 1628 BC, or more generally 1627–1600 BC have been heralded (but in some cases subsequently abandoned) as the date of the eruption on the basis of radiocarbon dating (in some cases combined with presumed ice-core or dendrochronological evidence). All such attempts encounter 1) the inherent difficulty of radiocarbon measurement, 2) the problematic nature of calibration and the resulting uncertainty in calibration curve data, and 3) the obdurate obstacle presented by the oscillation of the calibration curve during the late 17th and 16th centuries BC.

C.1) Inherent problems including pretreatment, regional variation, intra- and inter-year variation, seasonal variation, climate effects and contamination by ^{14}C-deficient carbon

High-precision Accelerator Mass Spectroscopy (AMS) radiocarbon laboratories today can measure the radiocarbon content of a single sample to within a 60-year range BP (Before Present), prior to calibration against a decadal measurement of a tree with rings of a known dendrochronological date (Manning 2006–2007: 60; pers. comm. of 16 September 2008). Repeated measurements may narrow the range. Pretreatment of samples, particularly with regard to the removal of humic acid, may occasionally present difficulties, even for modern high-precision laboratories.

Measurement differences between high-precision labs continue to exist. For example, "[o]verall, comparing the Oxford (OxA) versus Vienna (VERA) data on the same samples (using the pooled ages for each individual laboratory where they re-measured the same sample, thus n=17), we find an average offset of -11.4 ^{14}C years. The standard deviation is, however, rather larger than the stated errors on the data would imply at 68.1. This indicates that there is an unknown error component of 54.5 ^{14}C years" (Manning et al. 2006b: 5). Moreover, "the possible likely typical unknown error component of around 14 ^{14}C years found between Oxford and Vienna is about as good as can be expected in such an inter-comparison given the typical level of offsets found in inter-laboratory comparisons even between the high-precision laboratories" (Manning et al. 2006b: 5. For inter-laboratory differences generally, see Scott 2003; Reimer et al. 2004). A mean offset of 27 ±2 ^{14}C years on samples divided between Heidelberg and Seattle was unfortunately never resolved; rather the differing data sets were combined in the calibration curve (Reimer et al. 2004: table 1). Other examples of significant unresolved inter-lab differences on measurements of the same wood exist. For example, earlier measurements of bristlecone pine in Tucson were subject to reexamination by the radiocarbon laboratories in Heidelberg, Groningen, Pretoria, and Seattle and produced a mean difference of 37 ±6 ^{14}C years (Reimer et al. 2004: 1033). Radiocarbon determinations still produce "outliers" with some frequency, with occasional measurements a century apart on samples divided between two or more high-precision labs, as in the Turin Shroud measurements of samples divided between Arizona, Oxford, and Zurich (Taylor 1997: 84–85).

The decadal measurements of the calibration curve necessarily mask to some degree both intra-year as well as inter-year variability. The intra-year difference in radiocarbon ages between the summer high and winter low has been said to vary generally between 8 and 32 radiocarbon years (Housley et al. 1999: 167; Levin et al. 1992: 503–518; Levin and Hesshaimer 2000: 69–80. The analyses cited are based on simplified models utilizing postindustrial measurements, which are affected by industrial emissions [Suess effect]. Keenan [2004] argues that measurements of preindustrial samples show that the difference can be far larger than 32 years).

Intra-year seasonal differences in measurements may be compounded by regional climate differences, which in turn may be magnified greatly during periods of climate change. The difference between the late winter–early spring growing season for seeds in Egypt and the late spring–early summer growing season for European trees would push the Egyptian determinations toward dates older than actual dates after calibration based on determinations from German and Irish oaks, for example. Whereas the German oaks of the calibration curve lie at around 50° latitude and the Gordion logs and Theran seeds and trees at around 40°, Cairo in Egypt lies at 30° latitude, and the growing season in Egypt includes the winter–spring ^{14}C minimum (Keenan 2004). Indeed, even many staunch advocates of the superiority of radiocarbon-based chronologies agree that determinations from the Gordion logs of the Anatolian floating tree-ring chronology give calibrated dates quite different from determinations from German and Irish trees on which the calibration curve is based for what are believed on substantial grounds to be the same decades at the end of the ninth and first half of the eighth centuries BC. They attribute the result to changes in solar radiation and a consequent cold period latening growing seasons in Anatolia in the period (Kromer et al. 2001: 2531; Manning et al. 2001: 2533–2534; Manning et al. 2006c). Whether a cold period occurred at any point in the decades preceding the Theran eruption is of course unknown.

A recent report that for the period AD 1600–1800 Turkish pines and Irish oaks show a seemingly trivial average difference of 1.02 years (Manning et al. 2006c) is potentially misleading with respect to the risks of regional variation, since in many decades the measurements differ by 20–30 years, sometimes in one direction and sometimes in the other, the opposing directions of the differences resulting in the seemingly trivial average difference. Moreover, the average difference should have been stated as 1.02 $\pm s$ years (where s = the standard deviation), a somewhat different matter. (I am grateful to D. Keenan for calling this point to my attention.)

Although the calibration curve was initially based on the premise that ^{14}C was distributed evenly in the earth's atmosphere (Reimer 2004), differences in radiocarbon measurements of decadal determinations of trees of the same known dates from the Northern and Southern Hemispheres—amounting to a mean difference of 41 ±14 years over the past 900 years, but with a variation between 8 and 80 years—have led to the recent creation of a separate calibration curve for the Southern Hemisphere. An Intertropical Convergence Zone is believed to act as a curtain between the hemispheres, preventing or delaying the mixing of atmospheric elements. (I am grateful to S. Manning for his reminder in this regard.)

While the principal reason for the lack of convergence of radiocarbon determinations between the hemispheres may be understood, the underlying cause or causes of the differences between Northern and Southern Hemisphere ^{14}C measurements and their relative significance are unclear. More of the Southern than the Northern Hemisphere is covered by water which retains ^{14}C-deficient carbon; accordingly, it has been suggested that this ^{14}C-deficient carbon is supplied to the atmosphere, and from the atmosphere to trees and plants (Lerman, Mook, and Vogel 1970; Knox and McFadgen 2001: 87). Radiocarbon measurements of marine mollusks from the Atlantic Ocean give dates typically 400 years older than their true ages because ^{14}C-deficient deep water supplies some of the carbon dissolved in the upper layers of the ocean (Facorellis, Maniatis, and Kromer 1998). The correction for this "reservoir effect" is typically 400 years, but it varies with location. It has also been proposed that the diffusion throughout the Southern Hemisphere via cold-water currents flowing northward of ^{14}C-deficient carbon from a source in the Weddell Sea in Antarctica may be a factor in the Southern vs. Northern Hemisphere difference (B. Kromer, pers. comm. of 9 November 2002). Living (or at least recently deceased) penguins in Antarctica appear to be 800 years old based on ^{14}C measurements (B. Kromer, pers. comm. of 9 November 2002). Such deep water reservoirs of terrestrial carbon have not been replenished with ^{14}C from the atmosphere and hence have older radiocarbon ages. Upwellings of ^{14}C-deficient carbon during El Niño or ENSO episodes have also been proposed as a causal agent of the hemispheric difference (Stuiver and Braziunas 1993: 296). Attention lately has focused on periodic warming and cooling cycles in the Pacific Ocean at approximately 60-year intervals (S. Manning, pers. comm.; Ministry of Environment, Government of British Columbia 2002). A hypothesis has been proposed to explain the phenomenon: because more of the Southern Hemisphere is covered by water, the cooling cycle may be more intense, and when the warming phase comes, more ^{14}C-deficient carbon may be released into the atmosphere than in the Northern Hemisphere in general.

Is the Southern Hemisphere phenomenon relevant to radiocarbon measurements from Thera? Certainly the ratio of water to land in the Aegean Sea is high, but is there evidence of a ^{14}C-deficient carbon source or sources, and a suggested mechanism or mechanisms for introducing ^{14}C-deficient carbon into the atmosphere? First, Thera and indeed the whole Aegean is notorious for vents containing ^{14}C-deficient carbon. Geothermal areas are known in the northern and central Aegean as well as along the Hellenic Volcanic Arc. A recent occurrence near the island of Melos was described as follows: "Every fumarole on the shore blew out. And the sea boiled as the gas came out with such force. Stunned fish came to the surface" (P. R. Dando, as quoted in Pain 1999: 41). Another major source of old carbon exists 5km NNE of Thera. After a visit to Thera in 1884, the traveler James Theodore Bent reported that the water in the caldera was almost at boiling heat in parts and contained bubbles of vapor, as a result of a recent minor eruption, and that the sulfur content was sufficient to remove the barnacles from ships' hulls (Bent 1966: 118).

On Thera itself, a study by F. Barberi and M. L. Carapezza concludes that "24 points of anomalous soil gas release or concentration have been identified... half in the northern area and half in the southern one" (1994: 340). The most recent detailed study (McCoy and Heiken 2000) reports that "manifestations of volcanism and concomitant hazards remain today with fumaroles, seismic activity, hydrothermal springs, and higher concentrations of helium and CO_2 in soils" (43) and that "high concentrations of helium and CO_2 are present in soils on central Thera" (48). Moreover, in volcanic areas groundwater may be saturated with ^{14}C-deficient CO_2, which may then diffuse through soil and into the air. Tests in Tuscany have shown that where groundwater reaches the surface at natural springs, nearby trees may give elevated ^{14}C ages (Saurer et al. 2003). (I am grateful to S. Soter for calling this article to my attention.)

Agricultural activity can release ^{14}C-deficient gases, and aquifers can contain significant amounts of ^{14}C-deficient carbon (Mörner and Etiope 2002: 193). Fumaroles send ^{14}C-deficient carbon into the atmosphere where it can be absorbed by the leaves of plants and trees. The soil gas in geothermal areas has elevated concentrations of old CO_2. Plants are known to acquire small amounts of carbon directly from the soil through their roots (Stolwijk and Thimann 1957; Skok et al. 1962; Geisler 1963; Splittstoesser 1966; Arteca et al. 1979; Yurgalevitch and Janes 1988).

One study of current short-lived plant material from Thera whose true age was about one year provided radiocarbon ages of 1390 and 1030 years before present (Bruns et al. 1980: 535 table 2). The plants were located near vents of ^{14}C-deficient carbon, which the plants had absorbed. The old carbon effect disappeared beyond a distance of 250m (Bruns et al. 1980: 534 fig. 1). Investigations of fields of ^{14}C-deficient carbon both in southern and northern Italy (Rogie 1996; Chiodini et al. 1999; Rogie et al. 2000; Cardellini et al. 2003) have shown much more widespread geographical effects, however, and there is no way of estimating the amount of such carbon released by the precursory activity of the Theran volcano preceding the major LC I/LM I event. (These examples illustrate the difference between measurement accuracy and date accuracy, which is another matter altogether and one not necessarily captured by stated radiocarbon error bands.)

Some have argued that the presence of ^{14}C-deficient carbon in samples would cause irregular effects and so cannot explain a purported pattern of radiocarbon determinations 80–120 years earlier than historically derived dates for the Theran eruption. No such pattern exists, however. Most determinations on Theran samples fit easily within the oscillating portion of the calibration curve (see below). For example, the most recent set of measurements of seeds from jars buried in the Volcanic Destruction Level on Thera, the best context imaginable, divided between the VERA laboratory in Vienna and the OxCal laboratory in Oxford, produced dates that were compatible with one exception with the historical chronology (Manning et al. 2006a;

2006b). The one exception formed half of a pair of seeds from the same jar, one of which provided an anomalously high ^{14}C age. (Given the more than two-sigma spread between the radiocarbon ages of the two seeds, a statistical case for exclusion of both determinations as incompatible could be made.) In the brief period of perhaps months between the preliminary major earthquake and release of gases and the final eruption, the chance of release of old carbon was in all likelihood heightened. The one other ^{14}C determination (Bronos 1a: Manning et al. 2006b) giving an anomalously high radiocarbon age was collected from an insecure context in the 1970s and the ^{14}C age measured then. The very few samples which provide earlier radiocarbon ages vary substantially; as a result, there exists a risk of biasing results by including in the database a sample with 1% ^{14}C-deficient carbon which adds about 80 years while excluding as an "outlier" a sample with 3% ^{14}C-deficient carbon which adds about 240 years. Moreover the ^{14}C-deficient carbon problem need not explain all of the small number of "early" ^{14}C determinations, given the other sources of uncertainty described above, including regional, seasonal, and climatic variation, all of which tend to produce measurements on Aegean samples higher after calibration than true dates. Other ^{14}C measurements, such as those from Trianda on Rhodes or Miletus in Anatolia, were taken from wood which may not preserve its original outer rings or which may have been in use for an unknown period, in either case making it impossible to date the context from the age of the wood.

C.2) Calibration curve problems in general

The calibration curve, by which radiocarbon measurements are converted to calendar date ranges through comparison with radiocarbon measurements of tree-ring segments of known date, is sometimes viewed as fixed and immutable. In fact the calibration curve is a fragile construct, "not a curve, but a probability band" (Manning 1995: 128), whose application requires both judgment and caution. The uneasy relationship between the 11-year and 25-year sunspot cycles and the decadal calibration curve data is one source of uncertainty. Such cycles are detectable within the curve (Attolini et al. 1993; Buck and Blackwell 2004: 1101). The resulting effect appears to vary over time and location. "Pacific Northwest Δ^{14}C values… contain an 11-yr cycle with an average amplitude of 1.40 $\pm$0.16‰(ca. 11 $\pm$1 ^{14}C yr). This amplitude differs significantly from the 11-yr cycle amplitude of 4.8 $\pm$0.6‰(ca. 39 $\pm$5 ^{14}C yr) found in Russian trees (Kocharov 1992) between AD 1600 and AD 1950" (Stuiver 1993: 68). (I am grateful to D. Keenan for reminding me of these citations.) In retrospect, it might have been preferable to construct a calibration curve based on 11-year segments matching the 11-year sunspot cycle. The IntCal98 curve relies largely on earlier, less accurate measurements, often on samples not subject to modern pretreatment regimes, while the IntCal04 calibration curve combines older measurements with more recent measurements by high-precision laboratories. Even with respect to modern determinations, however, the IntCal04 curve combines measurements from separate laboratories that are significantly different for the same decade. The difference in the case of a particular decade of old vs. new measurements is over 50 radiocarbon years in a number of cases, and recent German oak measurements differ from the IntCal04 determinations by up to 70 radiocarbon years (Manning et al. 2006c). The report of the 19th International Radiocarbon Conference of April 2006 concludes that "each group of researchers who provide data with potential utility for radiocarbon calibration curve estimation do their best to quantify their own internal sources of error and uncertainty and to report these in standard form. What they do not and cannot do is allow for sources of error or uncertainty that they are completely unaware of" (Bronk Ramsey et al. 2006: 792).

Questions include how much emphasis to place on the central area of a distribution given all the uncertainties of ^{14}C determinations discussed above, and the significance of the duration of the intersection between the radiocarbon age span obtained from a sample (e.g., a seed) and the radiocarbon segments of the calibration curve, once the fact of an intersection at two different areas of the calibration curve is observed.

Any single measurement results in a two-sigma (95.4%) probability band that is twice the width of the one-sigma band, e.g., $\pm$20 at one sigma, $\pm$40 at two sigma. Repeated measurements, however, may reduce the two-sigma range via statistical inference. Accordingly one frequently finds ranges stated in the nature of 1621–1605 BC at one sigma and 1627–1600 BC at two sigma, 95.4% probability. The statement of such ranges (particularly given the appearance of exactitude to the first decimal) frequently puzzles, and potentially misleads, humanists not trained in statistics, who assume that "95.4% accuracy" refers to date probability rather than measurement probability. In order for date probability to match measurement probability, it would be necessary for the calibration curve to be exact, which it is not; for the calibration algorithm that converts radiocarbon ages into dates to be exact, which it is not; for pretreatment and other laboratory procedures to be foolproof; and for offsets and variation to be absent. If, however, either the seed or other sample or the relevant decadal segments measured for the calibration curve contain humic acid or are affected significantly by inter-laboratory offsets, intra- or inter-annual variation, regional variation, or seasonal variation sometimes amplified by climate change, repeated measurement will not eliminate the problem, and accordingly measurement-indicated probability will diverge significantly from calendar date probability. Where ^{14}C-deficient carbon is present the divorce is total, for it is the date of the mingled carbon rather than the date of the sample which has been measured and provided with a probability estimate.

The international committee responsible for the preparation of the calibration curve published in 2004 (IntCal04) concluded that because the initial measurements of decadal or duodecadal segments of the calibration curve on wood of known date from long-lived German and Irish oaks were made decades ago with less sophisticated equipment and methods than exist today and depended on a very few measurements for each decade—some of which have since been recognized as erroneous (Wiener 2003: 382; 2007)—the Gaussian bell-curve-derived estimates of measurement accuracies, adopted initially as a default position in the absence of an agreed data-driven standard, should be multiplied at the one-sigma range by 1.3 for the Seattle lab and 1.76 for the Belfast measurements on German oak, for example. The IntCal04 Committee further decided to limit the impact of error in any particular decadal measurement by smoothing the calibration curve through incorporating into each decadal determination the measurements of the nearest 100 data points or observations, whether these observations came from repeated measurements of the same decade from the same piece of wood, the same decade from other pieces of wood, semi-decadal measurements, or measurements from individual annual rings within a decade. Accordingly the time span incorporated into each decadal determination can vary significantly depending on the density of the observations at a given point (Buck and Blackwell 2004: 1100. I am most grateful to Dr. Paula Reimer, the chair of the IntCal04 Committee and Director of the ^{14}CHRONO Centre for Climate, the Environment, and Chronology at the Queen's University Belfast, for clarifying this matter for me). The decision to smooth the calibration curve in this manner proved controversial, and it may be that in the next iteration of the calibration curve, expected in AD 2010–2011, the Random Walk model on which the IntCal04 curve is based will be replaced by a Markov Chain model resulting in less smoothing, particularly since many more decadal determinations from various high-precision laboratories will be available. The resultant modifications generally will not be substantial, but even small changes to critical decades in and surrounding the oscillating portion of the calibration curve in the 17th–16th centuries BC may be relevant to the debate about the dating of the Theran eruption, for example. The IntCal04 Committee also noted that for wiggle-matching purposes the actual data represented by the superseded IntCal98 curve, however flawed, might be preferred to the artificially smoothed date bands, and that "in the case of wiggle-matching of tree-ring sequences, the method is sometimes being pushed to the limits in all respects" (Reimer et al. 2004: 1037. For other critiques of the methodology of wiggle-matching, see Whitelaw 1996; Cavanagh quoted in Wiener 2003: n. 148; Wiener 2003).

The procedures which connect measurements to calibrated dates, such as those contained in the OxCal program, also deserve consideration here. Martin Aitken, the former Deputy Director of the Oxford Research Laboratory for Archaeology and the History of Art, noted that, "conversion to calendar date is confusing because of the irregular form of the calibration curve; the difficulty of translating error limits from one time-scale to the other is particularly acute and here we are inevitably in the hands of the statisticians" (Aitken 1990: 93). Unfortunately, statisticians using different approaches or models on the same data may produce significantly different results. A recent study of the dating of the Iron Age I to Iron Age II transition at sites in Israel (Mazar and Bronk Ramsey 2008) reports that two different Bayesian models (labeled C2 and C3) provided different date ranges, and warns of the sensitivity of Bayesian models to outliers, even where only one measurement at one site is at issue. The inherent, intractable nature of the difficulty presented is discussed in detail in Manning (1995: 127–129). Figures 1A and 1B illustrate the effect of vigorous smoothing on a reported calibrated radiocarbon date in one instance (Buck et al. 2006: 285; Buck was the statistician for the IntCal04 calibration curve project).

The degree of likelihood that the true calendar date of the sample measured falls within the years represented by the peak in Figure 1B remains at issue. In any event, neither statistical method is sufficient to capture the potential impact of factors such as variation exacerbated by climate shift or the presence of ^{14}C-deficient carbon in a sample.

C.3) The oscillating calibration curve of the late 17th and 16th centuries BC

The oscillation of the calibration curve results in similar radiocarbon ages corresponding to calibrated dates at about 1610 and around 1535–1525 BC, whether

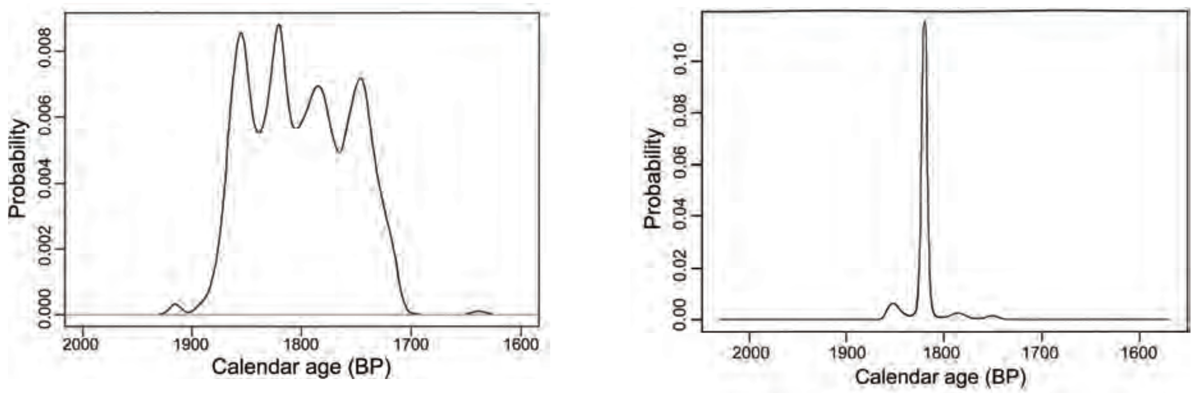

Figure 1: Posterior density for true calendar age θ_0 of a sample with radiocarbon age 1870 ±30. On left, (Figure 1A) Density from the traditional piecewise linear interpolation of the IntCal98 data. Right, (Figure 1B) Density after Buck et al. 2006 Random Walk/Bayesian modeling.

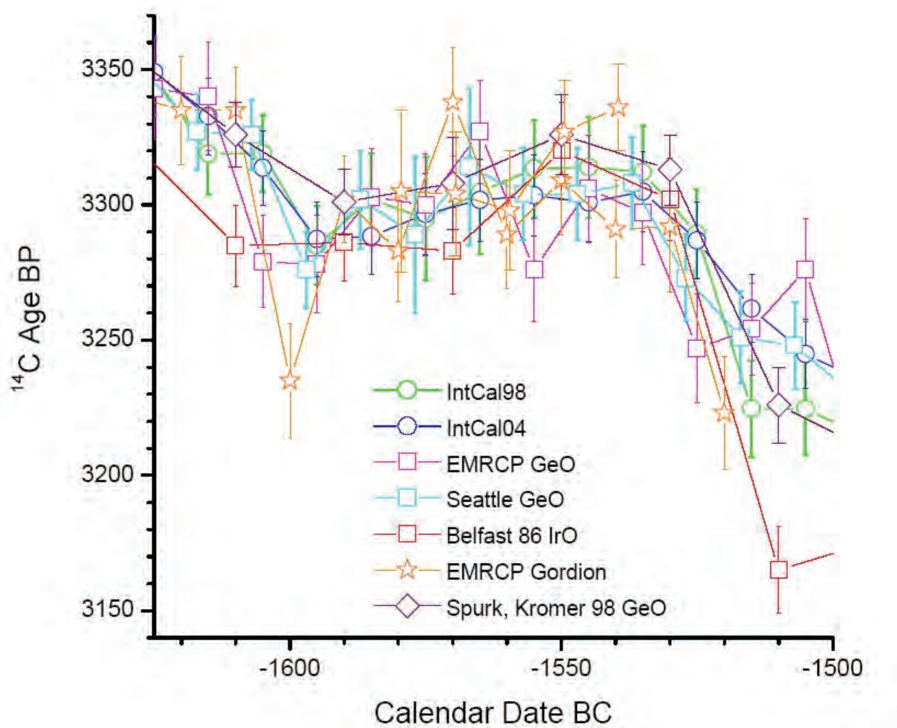

Figure 2: Comparison of the IntCal98 and IntCal04 calibration curves against the two major underlying datasets (the Seattle UWTEN data on German Oak [GeO] for this period, and the Belfast 1986 data on Irish Oak [IrO]) and against the EMRCP data for German Oak and Gordion Juniper, and previous Heidelberg German Oak data revised in 1998.

one uses, for example, 1998 measurements on German oaks or recent measurements on German oaks and the Anatolian logs from Gordion, as shown in Figure 2 (I am most grateful to S. Manning for forwarding this data and depiction). The 1998 German oak measurements were only about 10 radiocarbon years apart for calibrated ages of 1610 and 1530 BC (and this is reflected as well in the IntCal98 measurements for 1615 and 1535 BC); the East Mediterranean Radiocarbon Intercomparison Project (EMRCP) 2006 German oak measurements gave closely similar radiocarbon ages for determinations from the decades centered on 1605, 1555, and 1505 BC and separately for 1585, 1575, and 1535 BC, and the Project measurement of the Anatolian junipers from Gordion gave similar radiocarbon ages at 3335 BP for 1620, 1570, and 1540 BC, and only a minor difference of about 10 radiocarbon years between 1600 and 1520 BC. Both IntCal04 and the Seattle German oak measurements show nearly identical radiocarbon ages at 1595 and 1525 BC.

While the Gordion measurements are more geographically relevant to the dating of samples from Thera than Irish or German oak determinations, nevertheless Thera and Gordion lie in separate meteorological regimes, with Gordion strongly affected by winds from the northeast (Keenan 2002: 237 fig. 1; Reddaway and Bigg 1996: fig. 3). Location-dependent radiocarbon effects may differ accordingly. In connection with the data depicted in Figure 2, it is worth noting that research in the course of establishing the 1998 calibration curve disclosed a mean difference of 24.2 ±6 years between Belfast measurements of Irish oak and Seattle measurements of German oak for the critical years 1700 to 1500 BC (Wiener 2007). Manning et al. in their discussion of a ^{14}C measurement of a three-year tree twig preserved in the Volcanic Destruction Level on Thera which produced a date consistent with the historical chronology, observe that the sample may "reflect short-term higher amplitude and/or frequency variation in atmospheric ^{14}C ages not seen in the IntCal04 record for the period, which is both based on 10-year growth samples and smoothed" (2006b: 12).

C.4) Recent proposals to overcome the oscillation obstacle and their defects

Two articles in the 28 April 2006 issue of *Science* magazine address the problem posed by the oscillation. One (Manning et al. 2006a) focuses on radiocarbon determinations from before and after the period of oscillation to support a high chronology, long favored by Manning. Unfortunately, for the pre-oscillation period the article can only offer ^{14}C measurements which in each case provide at best a *terminus post quem* date. A piece of wood found at the Minoan site of Trianda on Rhodes produced rather incoherent determinations for its three decadal segments, with 80 years separating the central points of adjacent decades and outer rings which gave earlier dates than the inner rings. There is no way of knowing how many years separated the felling of the tree from the burial of the object—piece of furniture, shelf, beam, or whatever—from which the chunk of wood derived.

The second pre-oscillation data point is a piece of wood covered in Theran tephra from what the excavator, W.-D. Niemeier, believes was a throne in a shrine area at the Minoan site of Miletus on the coast of Anatolia. Whether the outer preserved ring represents what is called a "waney edge" indicating a point close to the felling date is not entirely clear (Bronk Ramsey et al. 2004: 327; Manning et al. 2006b), but in any event the period of time between the felling of the tree and the eventual destruction of the throne (or perhaps chair, chest, shelf, or beam) is unknown.

The Supporting Online Material for the *Science* article also republishes ^{14}C determinations from short-lived samples from the Theran Volcanic Destruction Level. Most fall within the oscillating portion of the calibration curve, as noted above. The few which do not each pose problems of context or measurement as noted above.

At the post-oscillation end, the article republishes dates from two Late Minoan IB destruction levels considerably later than the mature Late Minoan IA eruption on Thera. A prior claim (Manning et al. 2002: 741) that there existed a "unique explanatory solution" for the fact that the two sets of determinations on seeds from Myrtos-Pyrgos and Chania gave quite different dates for what were assumed (without any independent justification) to be destructions within the same or a few years of each other, namely that both destructions occurred within a steeply-sloped portion of the calibration curve, has been abandoned (Bronk Ramsey et al. 2004: 328) after it was noted (Wiener 2003: 391–392) that the vertical segment involved was an illusion based on a single erroneous measurement, pre-high-precision, in one laboratory. In fact, most LM IB destruction deposits give far later dates than those cited in the article, centering on 1460–1440 BC and thus are consistent with the historically well-established chronology (Soles 2004). An absolute date for the end of Late Minoan IB prior to the beginning of the reign of Tuthmosis III in Egypt between 1479 and 1468 BC, as proposed by Bronk Ramsey et al. (2004: 328–329), would indeed appear unlikely to historians conscious of the close links between LM IB Crete and Tuthmoside Egypt (see above). Finally, even a date around 1490 BC for a point in LM IB—even late in LM IB—would not in any event necessarily contradict a date for the Theran eruption between 1540 and 1525 BC.

The seriation analysis, where the time intervals between the various phases cannot be established independently, itself is highly dependent statistically on the correctness of the "boundaries" incorporated in the seriation—such as "Boundary 'End or Final LM IA to Start LM IB'; Event 'Early to Mid/Mature LM IB'; Boundary 'Early/Mid LM IB to Later LM IB' " (Manning et al. 2006b: 10)—many unrecognizable to archaeologists. (Potential hazards in the application of Bayesian analysis to radiocarbon dates are considered in Steier and Rom 2000 and Wiener 2003.) Of course data can be marshaled in various ways, for example by combining or alternatively discarding inconsistent measurements of samples or of segments of the calibration curve. "Bayesian analysis is not a 'cure-all'; it has costs, not least the specification of the prior. This is not easy and even in those situations where we think we are not making any strong assumptions, there may be hidden complications" (Scott 2000: 181). Indeed, the result obtained by Manning et al. is dependent on what data is included and what excluded. In fact, it would seem possible to apply "quasi-Bayesian" or "seriated sequence" analysis to achieve a result consistent with historical chronology by limiting the data bank to short-lived samples (i.e., excluding potentially old wood, as in the measurements from Trianda and Miletus employed in Manning et al. 2006a); eliminating determinations from samples of uncertain stratigraphy and/or displaying inchoate data, as in the Trianda sample; discarding inconsistent measurements of samples of known same date, as in one critical Theran Volcanic Destruction Level measurement; and employing instead as Bayesian boundaries the earliest observed existence of datable objects found in specific Aegean contexts, such as the White Slip I bowl from the Volcanic Destruction Level at Thera, or the Egyptian alabaster lid of a bowl bearing the cartouche of the Hyksos ruler Khyan in what seems clearly to be a Middle Minoan III deposit (P. Warren, pers. comm. 4 February 2005; Macdonald 2003: 40–41) at Knossos (rather than in a Late Minoan IB deposit as the Long Aegean Chronology would require). In short, the analysis presented in the Manning et al. article in *Science* and accompanying online data does not in itself present a persuasive case for drastically modifying the historically determined chronology for the Theran eruption and the Late Minoan IA period.

The second *Science* article presents radiocarbon determinations from four contiguous segments of a Theran olive branch found covered in tephra from the eruption (Friedrich et al. 2006a). Olive wood is difficult to date by standard dendrochronological methods, but an examination of the olive branch by X-ray computer tomography is said to have detected 72 indications, which the investigators assume represent annual rings, with a maximum counting error of ±16 rings for the entire estimated 72-ring sequence, but only ±3 rings for the final estimated 12-ring segment. The authors further state that a 50% difference in ring count would only increase the calibrated date limits of the radiocarbon determinations of the final segment (1621–1605 BC at one sigma, 1627–1600 BC at two sigma) by a decade. The Supporting Online Material for the article notes that if the IntCal98 calibration curve which utilizes the actual unsmoothed decadal measurements is employed, then the lower limit of the latest segment may drop down to c. 1575 BC at two sigma. It is accordingly pertinent that recent high-precision measurements of the calibration curve data from the Gordion logs, geographically the closest calibration curve data to Thera, give both 1) inconsistent measurements for the decade centered on 1580 BC and 2) a 1580 BC measurement indistinguishable because of the oscillating curve from the decade centered on 1530 BC (see Figure 2). Indeed, the radiocarbon ages of the two later segments of the olive branch encompass this oscillation whichever calibration curve is employed. The earlier segments of the rings, however, provide ^{14}C ages which on first impression fall before the oscillating portion of the calibration curve and thus offer support to a higher chronology, assuming no significant difference in ring count, the absence of climate/regional distortion, and the absence of ^{14}C-deficient carbon in the earlier segment(s) of the branch, always a risk in the Theran environment.

A preliminary question arises from the uncertainty as to the number of calendar years represented by the rings or partial rings of an olive branch observed through X-ray computer tomography. The article assumes without discussion that the rings were formed annually, but Cherubini has observed that "olive wood, as the wood of other Mediterranean evergreen species (e.g., *Quercus ilex*, *Quercus suber*, *Arbutus unedo*), may have one ring per year (at sites characterized by clear winter seasonality), two rings per year (at sites characterized by extreme dry conditions during summer and cold winter), no rings (at sites with very mild winter)" (pers. comm. of 19 April 2007, for which I am most grateful). Cherubini et al. (2003: 129) note that:

> ... [M]editerranean tree rings have seldom been used for dendroecological, dendroarchaeological or dendroclimatological purposes (Serre-Bachet 1985)....The main reason for this deficiency is the inability in many cases to identify clearly and date tree annual rings. Although the verification of the annual nature of tree rings is necessary

> for dendrochronological studies, the seasonal patterns of wood production are not yet well understood in plants lacking annual rings (Gartner 1995).

Of course if the Theran olive branch rings represent seasonal events two consequences follow: 1) the approximately 36 years thus putatively represented no longer present a progression of radiocarbon dates across seven decadal determinations; and 2) the purported wiggle-match to seven decades of the calibration curve disappears. If the earlier two segments of the olive branch are compressed into about a decade and a half as the consequence of rings formed seasonally rather than annually, then the risk of a wayward individual decadal data point in the calibration curve emphasized by the IntCal04 Committee arises.

The question of the number of years represented by the rings is also critical to the determination of the range of the probability bands around the estimated dates, for (as the authors acknowledge) it is only the presumed existence of annual rings that provides the "known time gaps between the samples [which] are the key to the high precision of the obtained calibrated ages" (Friedrich et al. 2006b). If the time gaps are uncertain because of the existence of seasonal rather than annual rings, the absence of rings in cultivated trees and/or the difficulty of interpretation of images of olive tree branches obtained by X-ray tomography, then the stated probability bands would require concomitant expansion. (Whether the OxCal program algorithms are sufficient to cover putative marked irregularities in ring counts is unclear.) As noted above, the central point of the distribution should not be given undue emphasis.

Perhaps the principal question respecting the olive branch stems from the propensity of olive trees to retain dead branches. Oliver Rackham, coauthor of *The Making of the Cretan Landscape* (1996) and *The Nature of Mediterranean Europe* (2003), has kindly provided the following comment in this regard:

> I don't follow the argument that the last growth ring of the wood specimen was contemporary with the eruption. The authors describe it as a 'branch,' but the pictures indicate a shattered radial fragment of a stem or major branch at least 40 cm in diameter. As we all know, many olive trees bear dead branches and fragments of branches, and I would not rule out the possibility that some of these might last 100 years after they died. The tree itself may have been alive when it was buried, but not all its limbs were necessarily alive or even recently dead (pers. comm. of 11 May 2008).

Harriet Blitzer, the leading specialist in the ethnography of preindustrial Cretan agricultural practice and author of "Agriculture and Subsistence" in *The Plain of Phaistos* (2004) concurs, stating that:

> Certain parts of a mature tree may die and other parts of the same tree may continue to grow and bear fruit. The decision to prune the dead branches is based in part on the overall structure of the tree (its stability and balance) and on whether the dead sections prove an obstacle to further growth in other parts of the plant. In many cases, among older trees, there are massive dead branches that have been left untouched for the above reasons. In those instances, the remainder of the tree is alive, growing and producing fruit (pers. comm. of 23 July 2008; see also Blitzer forthcoming).

It is worth noting that the radiocarbon date of 1613 ±13 proposed for the last segment would fit exactly the textual cum archaeological date for the Seismic Destruction Level at the beginning of LC I, an event which could have caused the death of the branch.

Unfortunately, the Theran olive branch covered in tephra from the eruption is for the moment that dreaded scientific phenomenon, a singleton. Both intensive remeasurement of the existing branch (preferably by a different radiocarbon laboratory) to determine whether the initial measurements are replicable and the location and measurement of an additional branch or branches are critical desiderata.

Conclusions

1. Establishing dates for the massive eruption of the volcano on Thera and for the Late Minoan IA period, the acme of Minoan civilization, is of prime importance for understanding both the internal development of Minoan civilization and its relations to the cultures of Egypt and the Near East.

2. A rich interlocking of texts, archaeology, interconnections between societies, and Egyptian astronomical dates limits the eruption, which occurred in a mature or final stage of LM IA, to the range of c. 1545–1495 BC, with the highest likelihood no earlier than c. 1525 BC, a year which also provides evidence of a climate-forcing event in tree rings at various places and in the Greenland ice (Wiener 2006a: 323). Tree-ring and ice-core indications of a volcanic event at 1571–1570 BC (Wiener 2006a: 320) are at the extreme upper limit (and many would say well beyond the upper limit) of an archaeologically conceivable date.

The higher a proposed date above 1525 BC, the harder it becomes to reconcile with the historical evidence; the lower a proposed date below 1525 BC, the harder it becomes to reconcile with the ^{14}C evidence.

3. Neither ice-core nor dendrochronological examination provides direct evidence of the Theran eruption.

4. The sometimes problematic nature of radiocarbon measurement, calibration, and statistical inference concerning their intersection constrains to some degree chronological conclusions based on ^{14}C determinations. The oscillating calibration curve between 1620 and 1520 BC remains a major obstacle to radiocarbon dating for this period. Overly optimistic assumptions about the dependability, accuracy, and precision of measurements of samples and of the boundaries of the calibration probability band against which they are compared are common.

5. Neither the seriated sequence analyses published to date nor the data obtained from the single Theran olive branch covered in tephra yet provide a convincing argument for moving dates for Late Minoan IA and the Theran eruption upward by 70–100 years. "Extraordinary claims require extraordinary evidence," said Carl Sagan (1979: 62), but thus far such evidence in support of an Aegean Long Chronology is lacking.

Accordingly, the separation of "the two cultures" in seeking an absolute chronology for the beginning of the Aegean Late Bronze Age persists.

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