The state of the debate about the date of the Theran eruption

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The primary aim of this paper is to present a critical review of the proposed scientific evidence for the date of the Theran eruption. A brief preliminary summary of the textual and archaeological evidence for the date is in order, however, to establish the cogent nature of the case which any purportedly contradictory scientific evidence must overcome.

First, Egyptian dates based on a rich interweaving of texts, both public and private, and supplemented by interconnections with securely dated rulers in the Near East and astronomical observations, are solid back to the beginning of the New Kingdom between 1540 and 1525 BC, and cannot move by more than two decades through the preceding century of the Hyksos Period.[1]

Second, chronological interconnections with Thera and the Aegean world have been established through multiple finds in good stratigraphic contexts in Egypt, the Near East, Cyprus, and the Aegean. For example, it is hard to imagine that a Cypriot White Slip I bowl from the Volcanic Destruction Level at Thera, a type nowhere attested earlier than the beginning of the New Kingdom in Egypt or at most no earlier than about 1560 BC, could have arrived in Thera prior to *c.* 1613 BC. The bowl shows evidence of use and repair in antiquity, and according to the leading specialists is not stylistically early in the sequence of White Slip I pottery.[2] Under the circumstances, about 1525 BC seems the earliest reasonable date, even if the bowl was one of the first such ever made and traveled quickly. The chronological horizon of White Slip I seems well-fixed, moreover by the fact that earlier Cypriot wares appear in the established order in earlier strata at Tell el-Dabᶜa, and by the thousands of sherds of Cypriot 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 the Near East, for example at Tell el-ᶜAjjul and at Ashkelon,[3] in Rhodes and in Cyprus in contexts including Minoan LM IA pottery.[4] At Palaepaphos-Teratsoudhia on the western coast of Cyprus one tomb contained not only sherds of White Slip I and LM IA pottery (the same association seen at Thera), but also a serpentine vessel bearing the nomen and prenomen of Ahmose, the first pharaoh of Dyn. XVIII in Egypt, who becomes pharaoh on the death of his brother Kamose between *c.* 1540 and 1525 BC.[5] The Aegean Long Chronology with a date for the Theran eruption of 1613 ±13 BC requires LM IA to end *c.* 1580 BC at the latest, which in turn would require either that the LM IA vases placed in the tomb were all heirlooms and that the White Slip I vases were of an earlier date than White Slip I vases known from anywhere else, or that the tomb had been reopened to deposit the Egyptian serpentine vessel about 50 years after the deposit of the LM IA vessels. At Trianda in Rhodes, Cypriot White Slip ware appears only above the tephra layer of the Theran eruption.[6] While any individual object may be an heirloom or of uncertain context, large numbers of potsherds and other objects are surely unlikely to arrive in foreign contexts regularly after 80 years' delay, or indeed 50 years' delay. Archaeological arguments seeking to explain such a delay by drawing a line

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[1] Wiener 2006b.

[2] Merrillees 2001, 90.

[3] Bergoffen 2001; Fischer 2003, 265.

[4] Eriksson 2001b.

[5] Eriksson 2001b, 63; Karageorghis 1990, 95, fig. 1, pl. XX:L.1.

[6] T. Marketou (pers. comm. 1 April 2007).

of demarcation separating Cyprus into western and eastern zones trading with different regions, otherwise unattested and matching no natural features, are rightly dismissed as wholly unconvincing by most archaeologists.[7] In any event, the chronological argument based on Egyptian interconnections does not by any means rest on Cypriot pottery, but includes Egyptian objects of well-established date found on Thera, Crete, and in the Mycenaean Shaft Graves at times closely related to the Theran eruption, and Aegean objects plus depictions of Aegean objects found in Egypt in contexts consistent with the standard chronology. The Theran evidence includes an Egyptian stone vessel found in the excavations of the Theran Volcanic Destruction Level by Christos Doumas published by Peter Warren and described by Manfred Bietak as no earlier in manufacture than the beginning of the New Kingdom between *c.* 1540 and 1525 BC, based on finds of similar stone vases to date.[8] Late Minoan I rhyta vase shapes are copied in local Egyptian clay or faience beginning in the New Kingdom.[9] If Late Minoan IA ended fifty years before the start of the New Kingdom as required by a 17th–early 16th century BC date for the eruption, then Egyptians were copying heirlooms which survived the Hyksos expulsion from Egypt, even though no such objects have ever been found at Hyksos sites.

We now move to the scientific claims for dating the eruption. An article in *Science* by Friedrich *et al.* asserts that there is evidence from ice cores and tree rings for a date 75–100 years earlier than archaeological dating for the Theran eruption.[10] There is in fact no such sustainable evidence. As to ice core dating, first the claim of significant similarity in rare-earth element composition between microscopic glass shards in a Greenland ice core lamination of *c.* 1642 BC[11] was challenged as not yielding convincing results.[12] Second, investigation disclosed that major differences in the bulk components of the Greenland ice particles and the Theran tephra made a common source unlikely.[13] Finally, it was shown that the published chemical composition of the ice core indication was 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. Other volcanoes, including the Hayes Volcano in Alaska, Mt. St. Helens in the Northwestern United States, and Avellino in Italy, also experienced 17th century BC eruptions.[14] Moreover, an analysis by Peter Fischer using state-of-the-art SIMS equipment at the Nordsim facility in Stockholm could find no trace of a volcanic eruption in the ice lamination of the succeeding year, notwithstanding the expectation that some such particles would have remained in the atmosphere.[15] In any event, there seems no basis for an assumption that every northern Hemisphere eruption must leave an acid signal in every square meter of the Greenland ice.[16] In sum, there is no sustainable ice core evidence for the Theran eruption.

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, 800 km due east of Thera, shows a growth spurt of indeterminable cause around 1642 BC, an impossibly early date for the Theran eruption on textual-archaeological 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 any later date for the eruption, for example a date compatible with the textual/archaeological evidence such as 1525 BC. Apparent correlations of ice core and tree-ring events in the same year or two in a number of lo-

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[7] Bietak 2004; Warren 2006; Wiener 2001; 2003; 2007.

[8] Further elaboration of the archaeological evidence may be found in Peter Warren, this volume.

[9] Koehl 2000; 2006, 342–5, 358.

[10] Friedrich *et al.* 2006.

[11] Hammer *et al.* 1987; 2001; 2003, 93.

[12] Pearce *et al.* 2004; Keenan 2003; Wiener 2007.

[13] Keenan 2003.

[14] Pearce *et al.* 2004.

[15] Fischer & Whitehouse 2004.

[16] Wiener 2003a; Robock 2000 and pers. comm.; Robock & Free 1995. The recent paper by Vinther *et al.* 2008, contends, however, that the analyses of chemical composition by Pearce and others, while cogent, do not completely rule out the possibility that the *c.* 1642 BC event in the Greenland ice cores was caused by the Theran eruption; contra Denton & Pearce, 2008.

cations around the globe, probably the results of major eruptions, occur at several dates, including 1571-70 BC and 1525-24 BC,[17] but the locations of the putative eruptions responsible for the suspected climate-forcing events are presently unknown.

We turn now to the radiocarbon evidence for dating the Theran eruption, focusing first on problem areas of radiocarbon dating in general and then specifically on proposed dates for the Theran eruption. The general challenges of radiocarbon dating include 1) the effect of seasonal variation reflecting differences in growing seasons between plants and trees in various areas, sometimes exacerbated by periods of cold climate; 2) the relatively small number of measurements of the tree segments of known date which compose the calibration curve, some from before the advent of modern high-precision laboratories, including measurements which have subsequently been acknowledged to be erroneous;[18] 3) questions arising from the assumptions underlying the claimed precision of results of the Bayesian or quasi-Bayesian probability analyses connecting sample measurements to the calibration curve; and 4) possible carbon reservoir contamination of samples by the presence of ^{14}C-deficient carbon from a) upwelling of seawater affecting the ^{14}C content of the atmosphere, b) groundwater, soil concentrations, or limestone formations, or c) volcanic vents.

We begin with the measurement of ^{14}C in laboratories. While measurements have improved greatly over the course of a generation, outliers and inconsistent measurements in samples divided between two or more high-precision labs still occur. Manning *et al.* in an article published in 2006 report that "[o]verall, comparing the Oxford versus Vienna data on the same samples, 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 [uncalibrated radiocarbon years]. This indicates that there is an unknown error component of 54.5 ^{14}C years". 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".[19] The recently published VERA laboratory in Vienna determinations for the Thutmoside period in Egypt, based on seeds found at Tell el-Dab^{c}a, differ markedly from all other radiocarbon determinations for this period, as well as from solid historical dates for the period.[20] The cause of the anomaly is unknown.

Comparison of measurements of short-lived samples such as seeds which may have a lifespan measured in weeks to the decadal or bi-decadal measurements of the trees which constitute the calibration curve necessarily confronts the fact that the intra-year difference in radiocarbon-age measurements between the summer high and winter low varies significantly, generally between 8 and 32 radiocarbon years, but with occasional higher variations. (The dilution of the atmospheric concentrations of ^{14}C and ^{13}C by large amounts of fossil fuel containing CO_2 largely lacking ^{14}C and ^{13}C in the past two centuries may limit the relevance of the proposed summer high versus winter low annual range with respect to premodern periods. Keenan suggests that 32 years may be a significant underestimate of the intra-year range.)[21] The growing season of Egyptian seeds is of course far different from that of the oaks in northern Europe on which the calibration curve is mostly based.

Calibration-curve determinations present significant further problems. The decadal measurements of the calibration curve necessarily mask to some degree both intra-year as well as inter-year variability, particularly since years of greater growth producing large rings will be always overrepresented in the decadal sample, and years of low growth producing narrow rings underrepresented. Anatolian trees give quite different radiocarbon dates from European trees of the same known dendrochronological date for the period 800–750 BC. A change in solar radiation at this time with a consequent cold period latening growing seasons in Anatolia

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[17] Wiener 2006a, 320–3; Salzer & Hughes 2007.

[18] Manning 2007, 108.

[19] Manning *et al.* 2006b, 5.

[20] Wiener 2006b; Marcus *et al.* n.d.

[21] Keenan 2004.

has been proposed as the cause by Manning *et al.* The inconsistent effect of the 11- and 88-year sunspot cycles also pose problems.

The problematic nature of the 1998 calibration curve was recognized by the international committee that produced the INTCAL04 calibration curve. The committee accordingly recommended that the Gaussian bell-curve-derived estimates of measurement accuracies should be multiplied at the one-sigma range by 1.3 for the Seattle measurements and 1.76 for the Belfast measurements on German oak.[22] The INTCAL04 Committee further decided to smooth the calibration curve by incorporating information from 100 surrounding data points for each decadal determination, in order to limit the impact of any single wayward decadal measurement. The number of years incorporated in this manner is inversely correlated to the density of information for any given decade. The calibration curve – really a probability band rather than a curve[23] – is not a fixed and immutable reference point, but rather a fallible human construct. 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".[24]

A recent experiment in Japan, where 5-year segments of a piece of cypress wood of known dendrochronological last-ring date of AD 389 were submitted for radiocarbon dating, provided a calibrated date range of 86% probability which was erroneous by a minimum of 72 years.[25] This result clearly illustrates the potential for confusion on the part of most consumers of radiocarbon dates stemming from the use of the term "probability" in this manner, with no disclosure of the underlying assumptions, particularly the assumptions concerning the accuracy and adequacy of the calibration curve measurements and the absence of climate factors and of ^{14}C-deficient carbon, discussed below. (The Japanese study also sounded a note of caution as to whether the utilization of a calibration curve largely based on German oaks was appropriate for the calibration of measurements of material from the islands of Japan also, a question relevant to the discussion below.) The warning of statistician Marian Scott is apposite: "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".[26] The utilization of ^{14}C determinations from different sites (and hence subject to different circumstances with respect to ^{14}C reservoir effects of various types, as well as different seasonal effects) as if they were repeated measurements from one horizon at one site is clearly problematic. Voutsaki *et al.* put the matter bluntly: "despite widespread practice, this procedure is not really statistically valid".[27] All such programs narrow the error bands depending on the number of measurements, a procedure sometimes justified with respect to first-order measurement uncertainty, but irrelevant and hence inadequate with respect to errors in the calibration curve, climate-magnified seasonal/regional variation, or local/regional variation stemming from the presence of ^{14}C-deficient carbon, whether from seawater or terrestrial sinks or other sources of ^{14}C-deficient carbon, including volcanic sources. Two-sigma error bands of ±15 or less with respect to calibrated dates for the second millennium BC rest on highly optimistic assumptions concerning the accuracy and precision of the calibration curve, the near perfection of the algorithms connecting sample measurements to the calibration curve, the absence of seasonal and climate-induced variation, and the nonexistence of ^{14}C-deficient carbon, from any source, in the samples tested. (The question of the potential presence of ^{14}C-deficient carbon is of particular significance in relation to measurements from Thera. Each 1% of such carbon in a sample moves the apparent date 80 years earlier than the true date.)

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[22] Reimer *et al.* 2004, 1034–6.

[23] Manning 1995, 128.

[24] Aitken 1990, 93.

[25] Imamura *et al.* 2007.

[26] Scott 2000, 181. Discussions of or relevant to the application of Bayesian statistics to radiocarbon dates may be found in Buck *et al.* 1996; Christen 1994; Christen and Buck 1998; Nicholls & Jones 2001; and Zeidler, Buck, & Litton 1998.

[27] Voutsaki *et al.* 2009.

One regional variation is already well established and accepted by the radiocarbon community. Recently a separate Southern Hemisphere calibration curve was published to reflect the fact that radiocarbon measurements from decadal tree segments of the same known date in the Northern and Southern Hemispheres differ by a mean difference of 41 ±14 years over the past 900 years, with a variation between 8 and 80 years. The underlying cause or causes of the differences between Northern and Southern Hemisphere ^{14}C measurements of samples of the same absolute date and their relative significance are unclear. (Wind belts known as the Intertropical Convergence Zone separate the two hemispheres and prevent atmospheric mixing.) More of the Southern than the Northern Hemisphere is covered by water, and water contains ^{14}C-deficient carbon which, when released into the atmosphere through periodic upwelling of deep-sea water and absorbed by trees and plants, makes calendar ages seem older than in fact they are. Such regional effects are not limited to the Southern Hemisphere, however. For example, similar regional offsets are proposed for Japan, either generally or for certain periods.[28] Stuiver and Braziunas describe how irregular water circulation oscillations of ^{14}C-deficient water,[29] some with a periodicity of 40–50 years, operate globally, "regionally distinct from ENSO but influencing Δ^{14}C in a similar manner" to these El Niño-Southern Oscillation episodes.[30] (They also consider whether a combination of low sunspot activity and resulting cold climate could cause a significant decrease in radiocarbon in certain periods in particular places.) Similar periodic upwelling of old carbon has been proposed for the Aegean, whether caused by the exchange of new cold deep water created annually in the northern Adriatic pushing up older water in the central Mediterranean, which then degasses as it depressurizes, or by the exchange of water with the Black Sea, rich in old carbon,[31] or in the form of periodic release of old carbon from the underwater vents discussed below. Reservoir effects have been reported for the Mediterranean including the Aegean in the early 20th century AD, but the evidence is scanty and nothing is presently known about earlier times.[32] Rapp and Hill note that "upwelling of deep water occurs near many coastlines" and that it "is affected by the shape of the coastline and the bottom topography, local climate, and wind and current patterns".[33] (Such upwelling is not a general phenomenon in the Eastern Mediterranean at present, however.)

Let us consider the position of the island of Thera in this light. Unlike the German oaks and central Anatolian juniper and pine trees which form the basis of the radiocarbon calibration curve, the trees and crops of Thera are surrounded by sources of ^{14}C-deficient carbon. Thera in particular and the Aegean in general are 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".[34] Another major source of old carbon exists 5 km north-northeast of Thera. The traveler Bent reported that in the 1880s a 10-days' stay in the waters off the Burnt Islands of Thera would clean the bottoms of ships without any effort on the part of the sailors.[35] One study showed that while the present levels of soil carbon dioxide (CO_2) on Thera are not uniformly high, 24 separate locations out the 76 yielded high levels, including one location close to Akrotiri.[36] The most recent detailed study by McCoy and Heiken, published in 2000, reports that "manifestations of volcanism and concomitant hazards remain today with fumeroles, seismic activity, hydrothermal springs, and higher concentrations of helium and CO_2 in soils"[37] and that "high concentrations of helium and CO_2 are present in soils on central Thera".[38]

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[28] Imamura *et al.* 2007; Ozaki *et al.* 2007.

[29] Stuiver & Braziunas 1993.

[30] Delworth *et al.* 1993.

[31] Keenan 2002.

[32] Reimer & McCormac 2002.

[33] Rapp & Hill 2006, 153.

[34] P.R. Dando, as quoted in Pain 1999, 41.

[35] Bent 1965, 118.

[36] Barberi & Carapezza 1994, 338.

[37] McCoy & Heiken 2000a, 43.

[38] McCoy & Heiken 2000a, 48.

With respect to the potential presence of ^{14}C-deficient carbon, a test by M. Bruns *et al.* in 1980 is worth noting. Their study of current short-lived plant material from Thera whose true age was about one year provided radiocarbon ages of 1390 and 1030 BP (years before present). The plants were located near a vent of such old carbon, which the plants had absorbed. The pronounced old-carbon effect of this particular vent, a point source as distinguished from a line (volcanic fault) source or a distributed source, disappeared beyond a distance of 250 m.[39] Strangely, some of the advocates of an Aegean Long Chronology have turned this one example into a universal rule, claiming that vents do not affect radiocarbon determinations except at close distances, and only by gross amounts. The literature shows just the opposite, with volcanic carbon vents in various areas in Italy affecting radiocarbon readings over many kilometres. A number of Italian studies have shown that historically securely dated deposits have produced anomalously high ^{14}C dates.[40] Further, agricultural activity can release ^{14}C-deficient carbon, as can groundwater flowing through ancient rocks and used for irrigation. N.A. Mörner and G. Etiope note that in the "Tethyan belt [which includes the Mediterranean region], high CO_2 fluxes are related to important crustal formations of … carbonate rocks [causing] high level of CO_2 concentration in ground and groundwater".[41] The great earthquake at the beginning of the Late Cycladic I period, 50 to 100 years before the Late Cycladic I–Late Minoan IA eruption, released quantities of magma through fissures, according to McCoy and Heiken.[42] The precursor phases of the final eruption would of course have released magma; and accordingly, seeds collected and stored during this period have an increased potential for a reservoir effect. We have no information whatever on the extent of magma release, if any, at any point in the past, let alone from the Theran eruption horizon.

The presence of ^{14}C-depleted carbon in the soil and groundwater of Thera (apart from the potential atmospheric presence due to upwelling of the surrounding deep-sea water) raises the question of the degree of carbon intake by trees and plants via roots rather than leaves. A number of studies have established the existence of such intake. With respect to pines, for example, a recent study in the journal *Tree Physiology* reports that "plants can acquire carbon from sources other than atmospheric CO_2, including soil-dissolved inorganic carbon (DIC). Although the net flux of CO_2 is out of the root, soil DIC can be taken up by the root, transported within the plant, and fixed…".[43] Similar behavior has been proposed for sycamore and willow trees.[44] Oliver Rackham, a leading specialist on olive trees, has noted that olive trees in particular spread massive roots in a search for water in dry climates.[45] As to seed-producing plants, all modern studies known to me suggest that plants take up at least a small amount of CO_2 through their roots,[46] and none reports they do not, notwithstanding certain assertions to this effect. Moreover, it is necessary to consider the possibility that the uptake of soil carbon saturates at a fairly low value to protect the health of the tree or plant (unless the tree or plant is overwhelmed by proximity to a volcanic vent). Plants and trees of course principally take up CO_2 through photosynthesis sites in their leaves. The effect of dense leaf canopies on radiocarbon determinations is the subject of a forthcoming study by S. Soter.

It is sometimes claimed that the presence of ^{14}C-deficient carbon in seeds or trees from Thera would necessarily result in gross and highly irregular distortions.[47] The Southern Hemisphere anomaly,

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[39] Bruns *et al.* 1980, 534 fig. 1.

[40] Rogie 1996; Chiodini *et al.* 1999; Rogie *et al.* 2000; Cardellini *et al.* 2003; Guidi *et al.* 1996; Turfa 2006; Chiodini *et al.* 2004; Gambardella *et al.* 2004; Minissale *et al.* 1997.

[41] Mörner & Etiope 2002, 193.

[42] McCoy & Heiken 2000a; Palyvou 2005, 177–8.

[43] Ford *et al.* 2007, 375. I am most grateful to Steven Soter for providing this reference. He notes that "the seedlings acquired about 0.8% of their carbon from soil DIC (CO_2 and its derivatives). Interestingly, the soil-derived carbon was partitioned unevenly among the various plant tissues, with a higher concentration in stems than in needles (leaves)" (pers. comm. 18 Nov. 2007).

[44] Teskey & McGuire 2007; Vuorinen & Kaiser 1997.

[45] Rackham 1965–1966. I am grateful to Peter Warren for this reference.

[46] Cramer 2002; Enoch & Olesen 1993; Cramer & Richards 1999. See also Saleska *et al.* 2007.

[47] Manning 2007, 111–2.

constrained within a range of 8–80 years over a 900-year span, indicates that, in some areas at least, discrepancies of less than a century are the rule rather than the exception. The Gordion log determinations, where a less-than-a-century discrepancy has been attributed to a low-solar-activity-induced cold-climate shift affecting the growing season and the absorption of sunlight during the late 9th–early 8th century BC, and the differences of up to a hundred years at around 680 BC in Japan are also in this range.[48] The 17th century BC is believed to have been a period of intense volcanic activity involving the eruption of Aniakchak and the Hayes Volcano in Alaska, Avellino in Italy, a volcano in Japan, and perhaps Mt. St. Helens in Washington state.[49] Research by Eddy describes a period of rapidly diminishing solar activity following a solar maximum which affected the ^{14}C absorption by trees during the period 1850–1700 BC, which may have affected climate and seasonal variation differently in Theran samples versus European and central Anatolian calibration curve measurements.[50]

Fortunately, awareness of such potential problem areas is becoming evident with the radiocarbon laboratory community. For example, C. Bronk Ramsey, the Director of the Oxford Radiocarbon Accelerator Unit, in his review of the current state of radiocarbon dating in the 50th anniversary issue of *Archaeometry* has carefully noted that 1) "[o]cean circulation and climate are obviously not in a steady state and so the reservoir offsets seen today will not be the same as those prevailing in the past (see, *e.g.*, Ascough *et al.* 2007)";[51] 2) "[u]nfortunately for dating applications, the oceanic circulation is an unwanted complication and it is usually only possible to make allowance for the spatial component of the variability";[52] and 3) "[i]n practice, the radiocarbon in any one region of the ocean will vary relative to the surface oceanic average. This variability, first seen in places where there is significant ocean upwelling (Monges Soares 1993), is much more likely to be the rule than the exception".[53] With respect to potential freshwater old-carbon reservoir effects, Bronk Ramsey observes that

> [h]ere, we know even less than we do about the oceans. Such freshwater systems not only act as reservoirs in their own right and exchange CO_2 with the atmosphere, but also incorporate carbon from carbonates of geological origin. This, in principle, means that the radiocarbon concentration can lie anywhere between the levels in the atmosphere and those of the bedrock (effectively zero).[54]

The potential reservoir effect of old carbon on radiocarbon dates is significant, both in general and with regard to the environment of Thera in particular. The problem is generally ignored in the publication of Aegean radiocarbon determinations, however.

A recent article by Manning contends that "at present there seems no even vaguely satisfactory explanation that could plausibly account for such a small and consistent/systematic 'old' age error/contamination for radiocarbon dates for the whole region at this time (and only this time)".[55] As we shall soon see, there is no credible radiocarbon dating evidence at this time for the whole region, and indeed for anywhere but Thera itself. As to the claim that such a Theran anomaly, if present, would exist "only at this time", there is no evidence at all for Theran radiocarbon dates at any other time. No radiocarbon samples were obtained in the early excavations of the Archaic or Hellenistic-Roman sites. Indeed, there is no evidence for human presence on Thera between the eruption and the 13th century BC.

With respect to determinations from the eruption horizon itself, the pre-olive branch evidence is ambiguous. Most radiocarbon measurements fall within the oscillating portion of the radiocarbon curve, which makes it impossible to distinguish dates between 1615 and 1525 BC. A few determinations give dates somewhat earlier, putatively for any of the myriad reasons discussed in this paper why some radiocarbon determinations provide misleadingly early dates. (Consider, for example, the dif-

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[48] Ozaki *et al.* 2007.

[49] Vogel *et al.* 1990, 535.

[50] Eddy 1977.

[51] Bronk Ramsey 2008b, 252.

[52] Bronk Ramsey 2008b, 252.

[53] Bronk Ramsey 2008b, 252.

[54] Bronk Ramsey 2008b, 252–3.

[55] Manning 2007, 111.

ference between Oxford measurement OxA 1552 at 3390 BP ±65 and OxA 1555 at 3245 BP ±65, or between Heidelberg Hd 5058/5519 at 3490 BP ±80 and Hd 6059/7967 at 3140 BP ±70.[56]) Sturt Manning summarizes the situation as follows:

> it is apparent from the parameters and data for the Thera "problem" ... that a solution may well be unlikely from the volcanic destruction level radiocarbon data alone. The data at hand either indicate strongly, or, in most cases, tend toward, a 17th century solution. However, it is undeniable that not all do, and that the radiocarbon "gap" between 17th century certainty, and 17th/16th century ambiguity, is all of about 20–30 radiocarbon years. This span is about the same as the best measurement precision available today for Accelerator Mass Spectrometry determinations—the source technology for nearly all the modern Thera radiocarbon ages. Hence one is operating on the limits of precision. And even small laboratory offsets, or variations caused in sample pre-treatment regimes, could become relevant in pushing data into, or out of, the ambiguity threshold. Hence we hit an impasse. And a skeptic is justified to be so.[57]

Numerous other bases for skepticism, from the problems of pretreatment and inter-laboratory measurement differences, to the fragile and uncertain nature of the calibration curve, to the effects of seasonal, regional and climate variation, to the problems inherent in the Bayesian algorithms connecting ^{14}C measurements to the calibration curve, to the potential presence of ^{14}C-deficient carbon, have been considered above. Statements of radiocarbon-measurement ranges in the nature of ±13 for Bronze Age dates should come with caveats regarding all these potential sources of error.

The claim that relevant radiocarbon determinations exist from "the whole region" (*i.e.*, from Trianda on Rhodes, Miletus in Anatolia, and sites on Crete) supporting an Aegean Long Chronology have been shown to be faulty. The evidence from Rhodes consists of a piece of wood of insecure context which produced inconclusive measurements for its three decadal segments, with 80 years separating adjacent decadal segments and the outer segment providing earlier dates than an inner segment.[58] The evidence from Miletus comes from a piece of wood which the excavator believes probably came from a chair or throne in a shrine area.[59] The piece of wood was covered in Theran tephra, but there was no way of determining the age of the wood when the chair, throne or beam was made, and still less the age when it was destroyed. The Cretan claim rested in part on the single aberrant measurement by the Belfast lab which was incorporated into the calibration curve but has since been disavowed,[60] and in part on unjustified or erroneous assumptions concerning the number of LM IB destructions at Khania or the simultaneity of LM IB destructions on Crete.

Let us turn at last to the now-famous branch of an olive tree found by an Aarhus University team covered with tephra from the eruption on Thera. The Media Release of 27 April 2006 of the Faculty of Science of Aarhus University has caused some astonishment, for it cites Dr. Walter Friedrich as claiming that the Theran artist who painted the miniature fresco of the fleet scene depicted the effect of the tsunami as it was happening, and that this accounts for the damaged prow of one ship and the drowning naked men,[61] notwithstanding the fact that the image is a standard depiction of a defeated enemy, warriors are shown ashore, and all the other ships are upright. More importantly, the tsunami followed the major (Minoan C) phase of the eruption that deposited four meters of tephra over the site, by which time all the inhabitants had departed.[62]

Let us focus on the radiocarbon measurements, however, for they form the most substantial argument to date for a long chronology. The article by Friedrich *et al.* in *Science* states that radiocarbon dates were obtained for four successive segments of the branch, which had a total of about 72 rings; that the radiocarbon measurements fall in the right order with the inner rings giving older dates, and finally that the measurement of the latest segment

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[56] Manning *et al.* 2006b.

[57] Manning 2005, 111–2.

[58] Manning *et al.* 2006a; Wiener 2009.

[59] Niemeier 2005, 6–7.

[60] Manning 2007, 108; Wiener 2003a, 392.

[61] Friedrich & Heinemeier 2006.

[62] McCoy & Heiken 2000a.

gives a destruction date of 1613 BC, ±13 years, using the 2004 smoothed calibration curve (but possibly as late as 1575 BC if the 1998 curve is used and assumptions about the number of years represented by the rings relaxed).[63] Of course 1575 BC is within the oscillating portion of the calibration curve as we have seen, but the earlier segments of the branch are said to give dates earlier than the 1620–1520 period of oscillation. How persuasive is this evidence?

The first question which arises is whether the branch in question was living at the time of the eruption or had died and ceased to absorb ^{14}C earlier. Oliver Rackham, the coauthor of *The Making of the Cretan Landscape* (Rackham and Moody 1996) and *The Nature of Mediterranean Europe* (Grove and Rackham 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.[64]

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.[65]

It is worth noting that the radiocarbon date of 1613 ±13 proposed for the last segment would fit exactly the archaeological date (based on interconnections with Egypt, and estimates of the duration of the LM IA, LH I, and LC I periods) for the massive Seismic Destruction Level at the beginning of LC I, an event which could have caused the death of the branch.

With respect to the potential presence of ^{14}C-deficient carbon (prevalent at and around Thera as noted above) in the olive branch, we do not and cannot know anything about the pre-eruption location of terrestrial vents. Recent research indicates that a caldera existed prior to the Minoan period eruption, perhaps formed by an earlier eruption around 25,000 BC, but the extent of that caldera cannot be closely determined.[66] Accordingly, the statement made in the abstract of the paper by W.L. Friedrich and J. Heinemeier that the tree was growing at a distance of more than 2.5 km from what is today the active volcanic zone is irrelevant. Moreover, old carbon can exist outside the active volcanic zone, as noted above. Of course we can have little idea of the pre-eruption landscape, including whether the tree stood in proximity to a degassing vent or to a river or other water-source of ^{14}C-deficient-carbon contamination which would put dates older.[67] The propensity of olive trees to seek groundwater for nourishment and the potential presence of ^{14}C-deficient carbon in groundwater in a volcanic landscape have already been noted, as has the potential for upwelling of ^{14}C-deficient carbon from the sea surrounding Thera. A general discussion of the problems posed for radiocarbon dating by the reservoir effects of ^{14}C-deficient carbon from upwelling of seawater and from groundwater is now available in the 50th anniversary issue of *Archaeometry*.[68]

In sum, at present there are simply too many unknowns with respect to the radiocarbon evidence to solve the equation. The advice of Aristotle to look for exactitude in each class of things only so far as the nature of the matter allows (*Nicomachean Ethics*

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[63] Friedrich *et al.* 2006.

[64] O. Rackham, pers. comm. of 11 May 2008.

[65] Pers. comm. 23 July 2008; see also Blitzer forth.

[66] Heiken *et al.* 1990.

[67] Yu *et al.* 2007.

[68] Bronk Ramsey 2008b.

1094b 23–27) remains sound and is applicable here. The radiocarbon-dated olive branch for the moment is 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. We hope for further discoveries. "Extraordinary claims require extraordinary evidence", said the scientist Carl Sagan.[69] The scientific evidence, which now consists significantly of the radiocarbon measurements from the single Theran olive branch, does not seem sufficient in light of all the areas of uncertainty described to shift the balance of probability against the well-established text-plus-interconnections-based Aegean Chronology.

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[69] Sagan 1979, 62.