RADIOCARBON DATING OF THE THERAN ERUPTION:

PROBLEMS INHERENT AND PROBLEMS CORRECTABLE

Running Title: Radiocarbon Dating of the Theran Eruption

Malcolm H. Wiener
The Institute for Aegean Prehistory
66 Vista Drive
Greenwich, CT 06830
mhwiener@villacandia.com
Phone: (203) 862-9334
Fax: (203) 625-0782

Jason W. Earle
The Institute for Aegean Prehistory
66 Vista Drive
Greenwich, CT 06830
jearle@instap.org

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Abstract

Today, there exists a widespread belief that certain radiocarbon dates from Late Bronze Age sites in the Aegean are in conflict with dates derived from Near Eastern and Egyptian texts, Egyptian astronomy, datable deposits of pumice and tephra from volcanic eruptions and numerous archaeological interconnections between Egypt, Cyprus and the Aegean. Attempts to date the Late Bronze Age eruption of the volcanic island of Thera (Santorini) provide an important example. In assessing these dates, this paper highlights a number of problems of ^{14}C *dating.*

Inherent problems include regional variation evident in some periods in their significantly different radiocarbon year measurements of tree segments of known dendrochronological range between trees from Germany and from central Turkey, a possible *"island effect," and especially the possible presence in samples of ^{14}C-deficient carbon resulting from gas emission fields such as those which exist over large parts of Italy or from volcanic point, line or area sources, or from upwellings from carbon reservoirs in sea water, and the hardwater effect resulting from sample contact with carbonates such as limestone.*

Correctable problems include a flaw in major calibration programs, which narrow reported error ranges solely in response to the number of measurements made irrespective of the consistency, inconsistency, or gross disparity of the radiocarbon ages obtained from the samples measured and the unsatisfactory manner in which radiocarbon measurements are frequently presented to the archaeological community.

Introduction

Improvement in communication between scientists providing radiocarbon dates and other chronologists, including archaeologists, historians, dendrochronologists, astronomers and mineralogists sourcing pumice and tephra, is the goal of this paper. The achievements, problem areas, and limitations of each discipline and method should be clearly communicated to chronologists of all disciplines.

We discuss the intense controversy about the date of the Bronze Age eruption of Thera (Santorini) (Fig. 1) because it illustrates clearly the major problems of archaeological radiocarbon dating and the lack of adequate communication between disciplines and because determining the date is important to our understanding of the interconnections between the major civilizations of the second millennium BC in the Eastern Mediterranean, and of the development of Aegean civilization. The massive eruption destroyed all sites on the island, a principal node on Aegean trade networks, and had a profound impact on the Minoan civilization centered in

Crete. The attempted dating of samples from the Volcanic Destruction Level at the harbor site of Akrotiri on the south coast of the island of Thera benefits from the fact that there can be no doubt as to the context, but suffers from the oscillating nature of the calibration curve, derived for the most part from decadal measurements of German, and to a lesser extent Irish, trees, which provide similar radiocarbon measurements at c. 1615 BC and 1525 BC. Certain proposed radiocarbon dates of material from the Volcanic Destruction Level would place the eruption just before the beginning of the oscillation at c. 1615 BC, a result incompatible with the traditional chronological date c. 1525–1500 BC. The traditional chronology is based on Egyptian and Near Eastern historical and astronomical records via numerous archaeological interconnections, including finds of pumice and tephra from the Theran eruption in closely datable contexts, whereas earlier archaeological contexts contain pumice from volcanoes in the Dodecanese known to have erupted at earlier dates.[1]

Problems of Radiocarbon Measurement

Inter-laboratory variation in measurements of ^{14}C in divided samples, while significantly reduced in general recently, continues to exist. A mean offset of 27 ±2 radiocarbon years on samples divided between the Heidelberg Radiocarbon Laboratory and the Quaternary Isotope Laboratory at the University of Washington, Seattle was unfortunately never resolved.[2] The inter-laboratory offset between the Oxford Radiocarbon Accelerator Unit and the VERA laboratory in Vienna averaging -11.4 radiocarbon years, but with a standard deviation of 68.1 radiocarbon years, indicating according to the investigators an unknown error component of 54.5 radiocarbon years,

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[1] These issues have been discussed in numerous articles (e.g., Wiener 1998; 2001; 2003a; 2003b; 2006a; 2006b; 2007). The most recent exchanges in the debate over the dating of the Late Bronze Age Theran eruption are: Wiener 2009a; 2009b; 2009c; Manning et al. 2009; Friedrich et al. 2009.

[2] Reimer et al. 2004, table 1.

also remains unexplained.[3] Unresolved disparities in measurements of trees of known dendrochronological date occur among logs from the same site (e.g., Gordion in Turkey for the years 1580, 1570 and 1560 BC); within measurements from trees in the same geographic area (e.g., two forests near the Rhine River at 1550 BC); and between the trees from Germany which form the backbone of the calibration curve and the trees from Gordion in Turkey in a number of periods (e.g., c. 1325 and 1225 BC, 1080–990 BC and especially between 850 and 750 BC, when the *average* offset is 28.8 ±26.3 radiocarbon years).[4] When radiocarbon measurements of trees of the same known dendrochronological date differ markedly, at least one of the measurements has provided an erroneous date; whereas agreement between two measurements provides no guarantee against error in both.

Intra-year seasonal variation in the production of ^{14}C also affects radiocarbon measurements. The difference between the summer high and winter low today generally ranges between eight and thirty-two radiocarbon years, and may exceed this range. Seasonal variation prior to the impact of industrialization on the atmosphere may have been greater.[5] Radiocarbon measurements of seeds of known date collected in Egypt between AD 1700 and 1900 disclosed an offset of 19.5 ±5 calibrated years earlier than calibration curve dates for this period.[6] The result raises the question of whether an adjustment with respect to Aegean measurements is required as well. In addition, radiocarbon measurements of decadal tree segments with years of greatly varying ring thickness may have only a loose connection to measurements of seeds with brief growing seasons within a single year.

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[3] Manning et al. 2006b, 5.

[4] Kromer et al. 2010, 875–6.

[5] Keenan 2004, 102–3; Housley et al. 1999, 167; Levin et al. 1992; Levin and Hesshaimer 2000.

[6] Dee 2010.

Reservoir Effects

Reservoir effects of various kinds present major problems with regard to Aegean radiocarbon measurements. Periodic upwelling of deep seawater releases ^{14}C-deficient carbon into the atmosphere where it may be absorbed by plants, thus skewing measurements from coastal sites toward older dates.[7] A recent study of five-year Japanese tree-ring segments of known dendrochronological date from 1060 BC to AD 400 found that for some periods the radiocarbon dates obtained differed significantly from the calibration curve dates. The authors suggest an "island effect" as a possible cause.[8] Several studies suggest the possibility of upwelling of ^{14}C-deficient carbon from the Aegean, either via the periodic exchange of water with the Black Sea which is rich in ^{14}C-deficient carbon,[9] or the release of ^{14}C-deficient carbon from underwater volcanic vents, one of which is located 7 km north-northeast of Thera.[10]

The critical sources of ^{14}C-deficient carbon include volcanic and non-volcanic gas vents, geothermal fields, and general soil degassing.[11] In Italy the area of terrestrial CO_2 emissions stretches from Tuscany to Sicily, and from the Tyrrhenian Sea to the Apennines.[12] Similar emissions have been observed in areas of southern Italy, and on the volcanic island of Stromboli.[13] Reported radiocarbon dates from Italian sites whose historical contexts are clear are frequently 100–300 years too early.[14] At Sulphur Banks on Hawaii, three living tree ferns and one Ohia leaf growing one to five miles from a volcanic vent gave radiocarbon ages between 81

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[7] Rapp and Hill 2006, 153.

[8] Imamura et al. 2007. See also Ozaki et al. 2007; Ozaki et al. 2009. Sakamoto et al. (2009) note that with respect to radiocarbon dates from the Japanese archipelago "possible local offsets of the curve cannot be ignored." Stuiver and Braziunas (1993) describe how irregular water-circulation oscillations of ^{14}C-deficient water, some with a periodicity of forty to fifty years, operate globally.

[9] Keenan 2002.

[10] For vents near Melos, see Pain 1999, 41.

[11] Frezzotti et al. 2009.

[12] Frezzotti et al. 2009, 109.

[13] Rogie 1996; Chiodini et al. 1999; Rogie et al. 2000; Cardellini et al. 2003; Chiodini et al. 2004; Gambardella et al. 2004; Minissale et al. 1997; Carapezza et al. 2009.

[14] Turfa 2006.

and 303 years.[15] In addition, groundwater that has been in contact with soil degassing or with limestone, a notorious source of ^{14}C-deficient carbon, if absorbed by plants or consumed by living creatures, sometimes result**s** in measurements which provide dates that are older than true dates.[16]

Statistical Issues

The combination and calibration of radiocarbon measurements, based on Gaussian and Bayesian statistics and conventions employed in the various calibration programs, pose many issues. AMS laboratories employ different methods of analyses, few of which have been published. The chosen method can have a significant impact on the quality of the results. The commonly used standard error of the mean can be too small or too large by a factor of two, but on average is too small; moreover, radiocarbon intercomparisons assume a Gaussian distribution of the results even though this is known not to be the case.[17] Sometimes even the meaning of basic terms differs between laboratories. The OxCal, Calib and Demokritos Laboratory (Athens) programs differ, for example, in their use of "probability." In the OxCal program 80% probability means 80% of 100, whereas in the Calib program it means 80% out of the two-sigma standard deviation of 95.4%, and the Demokritos program is unique, generally giving broader ranges (in our view appropriately so), but sometimes producing very different results. Moreover, ^{14}C measurements generally do not conform to the "ideal" standard distribution; rather the actual distribution under extensive replication is wider than the quoted errors, even after the exclusion of outliers. The quoted error denotes at best the variability within the same measurement run.[18]

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[15] Chatters et al. 1969, Table II. Radiocarbon measurements from the 1960s are, of course, problematic.

[16] Mörner and Etiope 2002; Fischer and Heinemeier 2003; Rapp and Hill 2006, 149–50.

[17] Palonen et al. 2010, 948.

[18] Boaretto et al. 2005, 43.

Most importantly, the OxCal and Calib programs share a basic fault: the programs narrow the error range solely in response to the number of measurements made, irrespective of how consistent, inconsistent, or even wildly discordant the individual ^{14}C measurements may be. (The statistical issue was noted independently in another context by T. Jull.[19]) Of prime importance to the Theran debate are the 28 measurements of seeds found in the Volcanic Destruction Level at Akrotiri, which produced measurements whose reported central ages were as much as 250 years apart, with the total maximum width of the respective probability bands of course wider still. Measurements of the same species of seed provided central radiocarbon ages 215 radiocarbon years apart in the case of peas and 97 years apart in the case of barley. An analysis of the data by Manning et al. of this discordant dataset asserted a measurement precision, based on the fact that there were 28 measurements, of 3344.9 ±7.5 years![20] The claimed precision is essential to their conclusion that radiocarbon dates support unambiguously Manning's proposed Aegean Long Chronology because, as Manning has previously noted, any age in the 3320s BP is potentially compatible with historical dating in light of the oscillating calibration curve (Fig. 2).[21] With an error band of ±25 rather than ±7.5, a radiocarbon age of 3344.9 BP would be potentially compatible with a date for the eruption of c. 1525 BC, even without any correction for a seasonal/regional offset or reservoir effects from known sources on or near Thera.[22]

Ramsey has noted (pers. comm. of 30 December 2009) that there are two potential methods of addressing the problem within the OxCal program. The first is to insert a minimum range which the investigator—e.g., the archaeologist submitting the samples—regards as a

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[19] In Sharon et al. 2007, 9.

[20] Manning et al. 2006a; 2006b.

[21] Manning 2005, 108.

[22] Wiener 2009a; 2009b.

minimal acceptable error range, based on her/his understanding of the nature of the database. In practice this is never done, given the intrinsic uncertainty and the fact that archaeologists seldom understand the complex statistical issues involved. The second method suggested by Ramsey of addressing the problem inherent in the calibration program is to introduce an asymmetric adjustment to the error range toward older dates to allow for estimated local reservoir (and/or regional/seasonal) effects. Such putative effects are also impossible to quantify, however. Higham et al. note that measurement of bones poses particular problems with respect to reservoir effects, but that it is not possible to determine a suitable average correction factor.[23] (In considering the historical consequences of Eastern Mediterranean radiocarbon measurements, the authors of the present paper make allowance for an error range of ±20 years in any case, with an additional asymmetric allowance where there is reason to believe that a regional/seasonal variation or, more importantly, a reservoir effect, is likely—e.g., +20/-50 to -90 BP for certain measurements of Theran Volcanic Destruction Level material.) Of course it would be possible to employ the earliest plausible date indicated by the well-founded historical date range for the Theran eruption as a Bayesian boundary, but it is precisely this historical dating which the radiocarbon determinations in question are said to challenge.

A recent attempt by Friedrich et al. to date a branch from an olive tree found in the volcanic tephra on Thera c. 7 km from Akrotiri presents its own problems.[24] First, there is no way of knowing whether the olive branch was living at the time of the eruption. Aegean olive trees are often covered in dead branches, and some long dead, since their owners hesitate to remove them for fear of damaging the tree (O. Rackham, pers. comm. of 11 May 2008; H. Blitzer, pers. comm. of 23 July 2008). Second, the claim that the investigators have been able via

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[23] Higham et al. 2010, 653.
[24] Friedrich et al. 2006a; 2006b.

X-ray tomography to count year rings on the branch is severely challenged by reports from dendrological laboratories that rings of olive trees are impossible to count with any confidence. In blind tests no two laboratories could agree on the number of "rings" on olive tree branches recently collected on Thera; moreover olive trees do not display anything approaching annual rings even if agreement could be achieved on the number,[25] which vitiates also the wiggle-match to the calibration curve claimed by Friedrich et al. The fact that the four segments of the branch studied by Friedrich et al. gave radiocarbon measurements which descended in order is also not germane, since this would be true in any event—e.g., if the four segments each contained a 1% reservoir of ^{14}C-deficient carbon resulting in measurements c. 80 years too old, the measurements of the four segments would still descend in order.

Other Archaeometric Evidence for the Dating of the Eruption

Four hundred and fifteen samples of pumice and tephra from the Minoan eruption of Thera have been found at 19 sites in Egypt, the Levant, Cyprus and the Aegean, all of them from New Kingdom contexts, whereas the 27 examples of pumice from earlier contexts all come from non-Theran eruptions. The investigators note that if the Aegean Long Chronology were correct, "it would indeed be most peculiar a phenomenon that pumice from the Minoan Santorini eruption were abundantly available along the shores of the Eastern Mediterranean, yet for some reason had been left unnoticed and unused by the local inhabitants for 100–150 years."[26] At one of the sites, Tell el 'Ajjul near Gaza, Theran pumice, Egyptian New Kingdom pottery, and Cypriot White Slip I pottery similar to a bowl recovered from the Theran Volcanic Destruction Level are accompanied by five radiocarbon dates from seeds not affected by Aegean reservoir effects

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[25] Humbel 2009; Cherubini et al. 2003.
[26] Steinhauser et al. 2010, 408.

which center on c. 1525 BC., the historically and archaeologically appropriate date for the eruption, while only touching the Aegean Long Chronology eruption date of c. 1613 BC at the limit of the two-sigma range (Fig. 3).

Conclusions

Certain radiocarbon dates for the eruption of Thera may differ from the prevailing historical date range due to: 1) factors specific to the area of the eruption; and 2) problems inherent in the process of calibration and in the statistical packages currently in use. Specific factors include the oscillating nature of the calibration curve between c. 1615 and 1525 BC; the particular reservoir effects likely present in measurements of samples from volcanic Thera and to some extent from islands composed of limestone such as Crete; and to a lesser extent, seasonal/regional differences between Aegean seeds/trees and northern oaks. General problems include the inherent uncertainties of calibration and the problematic nature of the statistical procedures currently employed, which provide probability estimates whose error ranges are based solely on the numbers of measurements included, irrespective of their degree of consistency or (sometimes major) inconsistency, and which avoid entirely the potential asymmetric bias toward older dates resulting from reservoir effects. Archaeologists submitting samples typically are unaware of the existence of such issues. Radiocarbon laboratories accordingly have a professional obligation to inform their clients clearly of the uncertainties and limitations of radiocarbon dating, both with regard to the particular samples submitted and in general. The duty is magnified when proposing a date range for an event as important as the date of the Theran eruption, which affects the chronology and history of the entire Eastern Mediterranean world.

References

Boaretto E, Jull AJT, Gilboa A, Sharon I. Dating the Iron Age I/II transition in Israel: first intercomparison results. Radiocarbon. 2005;47:39-55.

Carapezza ML, Ricci T, Ranaldi M, Tarchini L. Active degassing structures of Stromboli and variations in diffuse CO_2 output related to the volcanic activity. Journal of Volcanology and Geothermal Research. 2009;182:231-45.

Cardellini C, Chiodini G, Frondini F, Giaquinto S, Caliro S, Parello F. Input of deeply derived carbon dioxide in southern Apennine regional aquifers (Italy). Geophysical Research Abstracts. 2003;5 [cited 2010 Dec 9]. Available from: http://adsabs.harvard.edu//abs/2003EAEJA.....9927C

Chatters RM, Crosby JW, III, Engstrand LG. Fumarole gaseous emanations: their influence on Carbon-14 dates. Washington State University College of Engineering Circular. 1969;32:[about 9 p.]

Cherubini P, Gartner BL, Tognetti R, Bräker OU, Schoch W, Innes JL. Identification, measurement and interpretation of tree rings in woody species from Mediterranean climates. Biological Reviews of the Cambridge Philosophical Society. 2003;78:119-48.

Chiodini G, Frondini F, Kerrick DM, Rogie J, Parello F, Peruzzi L, Zanzari AR. Quantification of deep CO_2 fluxes from central Italy. Examples of carbon balance for regional aquifers and of soil diffuse degassing. Chemical Geology 1999;159:205-22.

Chiodini G, Cardellini C, Amato A, Boschi E, Caliro S, Frondini F, Ventura G. Carbon dioxide earth degassing and seismogenesis in central and southern Italy. Geophysical Research Letters. 2004;31:L07615.

Dee M. Investigating the accuracy of radiocarbon dating in Egypt: checks with samples of known age. Paper Presented at Radiocarbon Dating & the Egyptian Chronology; 2010 Mar 17-18; Oxford.

Fischer A, Heinemeier J. Freshwater reservoir effect in ^{14}C dates of food residue on pottery. Radiocarbon. 2003;45:449-66.

Frezzotti ML, Peccerillo A, Panza G. Carbonate metasomatism and CO_2 lithosphere–asthenosphere degassing beneath the Western Mediterranean: an integrated model arising from petrological and geophysical data. Chemical Geology. 2009;262:108-20.

Friedrich WL, Kromer B, Friedrich M, Heinemeier J, Pfeiffer T, Talamo S. Santorini eruption radiocarbon dated to 1627-1600 B.C. Science. 2006a;312:548.

———. Supporting online material for Santorini eruption radiocarbon dated to 1627–1600 B.C. Science 2006b;312 [cited 2010 Dec 9]. Available from: http://www.sciencemag.org/content/312/5773/548/suppl/DC1

———. Santorini eruption radiocarbon dated to 1627-1600 B.C: further discussion. In: Manning SW, Bruce MJ, editors. Tree-rings, kings, and Old World archaeology and environment. Papers Presented in Honor of Peter Ian Kuniholm. Oxford: Oxbow; 2009. p. 293-8.

Gambardella B, Cardellini C, Chiodini G, Frondini F, Marini L, Ottonello G, Zuccolini MV. Fluxes of deep CO_2 in volcanic areas of central-southern Italy. Journal of Volcanology and Geothermal Research. 2004;136:31-52.

Higham T, Warren R, Belinskij A, Härke H, Wood R. Radiocarbon dating, stable isotope analysis, and diet-derived offsets in ^{14}C ages from the Klin-Yar site, Russian North Caucasus. Radiocarbon. 2010;52:653-70.

Housley RA, Manning SW, Cadogan G, Jones RE, Hedges REM. Radiocarbon, calibration and the chronology of the Late Minoan IB Phase. Journal of Archaeological Science. 1999;26:159-71.

Humbel T. Jahrringidentifikation von Olivenbäumen auf Santorin zur Bestätigung von dendrochronologischen Datierungen der minoischen Eruption [Masterarbeit]. Zürich: University of Zürich; 2009. German.

Imamura M, Ozaki H, Mitsutani T, Niu E, Itoh S. Radiocarbon wiggle-matching of Japanese historical materials with a possible systematic age offset. Radiocarbon. 2007;49:331-7.

Keenan DJ. Why early-historical radiocarbon dates downwind from the Mediterranean are too early. Radiocarbon. 2002;44:225–37.

———. Radiocarbon dates from Iron Age Gordion are confounded. Ancient West & East. 2004;3:100–3.

Kromer B, Manning SW, Friedrich M, Talamo S, Trano N. 14C Calibration in the 2nd and 1st Millennia BC—Eastern Mediterranean Radiocarbon Comparison Project (EMRCP). Radiocarbon. 2010;52:875-86.

Levin I, Bösinger R, Bonani G, Francey RJ, Kromer B, Münnich KO, Suter M, Trivett NBA, Wölfli W. Radiocarbon in atmospheric carbon dioxide and methane: global distribution and trends. In: Taylor RE, Long A, Kra RS, editors. Radiocarbon after four decades: an interdisciplinary perspective. Berlin: Springer; 1992. p. 503-18.

Levin I, Hesshaimer V. Radiocarbon—a unique tracer of global carbon cycle dynamics. Radiocarbon. 2000;42:69-80.

Manning SW. Simulation and the Thera eruption: outlining what we do and do not know from radiocarbon. In: Dakouri-Hild A, Sherratt S, editors. Autochthon: papers presented to O.T.P.K. Dickinson on the occasion of his retirement. British Archaeological Reports International Series 1432. Oxford: Oxbow; 2005. p. 97-114.

Manning SW, Bronk Ramsey C, Kutschera W, Higham T, Kromer B, Steier P, Wild EM. Chronology for the Aegean Late Bronze Age 1700–1400 B.C. Science. 2006a;312:565-69.

———. Supporting online material for Chronology for the Aegean Late Bronze Age 1700–1400 B.C. Science. 2006b;312 [cited 2010 Dec 9]. Available from: http://www.sciencemag.org/content/312/5773/565/suppl/DC1

———. Dating the Santorini/Thera eruption by radiocarbon: further discussion (AD 2006-2007). In: Manning SW, Bruce MJ, editors. Tree-rings, kings, and Old World archaeology and environment. Papers Presented in Honor of Peter Ian Kuniholm. Oxford: Oxbow; 2009. p. 299–316.

Minissale A, Magro G, Vaselli O, Verrucchi C, Perticone I. Geochemistry of water and gas discharges from the Mt. Amiata silicic complex and surrounding areas (central Italy). Journal of Volcanology and Geothermal Research. 1997;79:223-51.

Mörner N-A, Etiope G. Carbon degassing from the lithosphere. Global and Planetary Change. 2002;33:185-203.

Ozaki H, Imamura M, Matsuzaki H, Mitsutani T. Radiocarbon in 9th to 5th century BC tree-ring samples from the Ouban 1 archaeological site, Hiroshima, Japan. Radiocarbon. 2007;49:473-9.

Ozaki H, Sakamoto M, Imamura M, Matsuzaki H, Nakamura T, Kobayashi K, Itoh S, Niu E, Mitsutani T. Radiocarbon dates of Japanese tree rings for 1060 BC-AD 400. Paper Presented at the 20th International Radiocarbon Conference; 2009 May 31-June 5; Big Island, Hawaii.

Palonen V, Tikkanen P, Keinonen, J. Using car4ams, the Bayesian AMS Data Analysis Code. Radiocarbon. 2010;52:948-52.

Pain S. Vents de Milos. New Scientist. 1999;103(2197):38-41.

Rapp GR, Hill CL. Geoarchaeology: the earth-science approach to archaeological interpretation. New Haven: Yale University Press; 2006.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, et al. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon. 2004;46:1029-58.

Rogie JD. Lethal Italian carbon dioxide springs key to atmospheric CO_2 levels. Penn State Earth and Environmental Systems Institute. News and Events: News Archives; 1996. [cited 2010 Dec 9]. Available from: http://www.eesi.psu.edu/news_events/archives/Lethal.shtml

Rogie JD, Kerrick DM, Chiodini G, Frondini F. Flux measurements of nonvolcanic CO_2 emission from some vents in central Italy. Journal of Geophysical Research. 2000;105(B4):8435-45.

Sakamoto M, Fujio S, Kobayashi K, Ozaki H, Imamura M. Radiocarbon dates of Japanese tree rings for 1060 BC-AD 400. Paper Presented at the 20th International Radiocarbon Conference; 2009 May 31-June 5; Big Island, Hawaii.

Sharon I, Gilboa A, Jull AJT, Boaretto E. Report on the first stage of the Iron Age dating project in Israel: supporting a low chronology. Radiocarbon. 2007;49:1-46.

Steinhauser G, Sterba JH, Oren E, Foster M, Bichler M. Provenancing of archaeological pumice finds from North Sinai. Naturwissenschaften. 2010;97:403-10.

Stuiver M, Braziunas TF. Sun, ocean, climate and atmospheric $^{14}CO_2$: an evaluation of causal and spectral relationships. The Holocene. 1993;3(4):289–305.

Turfa JM. Review of Bartoloni G, Delpino F, editors, 2005. Oriente e Occidente: metodi e discipline a confronto. Riflessioni sulla cronologia dell'età del ferro in Italia. Atti dell'Incontro di studi, Roma, 2003 ottobre 30–31. Mediterranea, 1 (2004). Pisa: Instituti Editoriali e Poligrafici Internazzionali. Bryn Mawr Classical Review 2006.08.10. [cited 2010 Dec 9]. Available from: http://bmcr.brynmawr.edu/2006/2006-08-10.html

Wiener MH. The absolute chronology of Late Helladic IIIA2. In: Balmuth MS, Tykot TH, editors. Sardinian and Aegean chronology: towards the resolution of relative and absolute dating in the Mediterranean. Proceedings of the International Colloquium 'Sardinian Stratigraphy and Mediterranean Chronology', Tufts University, Medford, MA, 1995 March 17-19. Studies in Sardinian Archaeology 5. Oxford: Oxbow; 1998. p. 309–19.

———. The White Slip I of Tell el-Dab'a and Thera: critical challenge for the Aegean Long Chronology. In: Karageorghis V, editor. The White Slip ware of Late Bronze Age Cyprus. Proceedings of an International Conference Organized by the Anastasios G. Leventis Foundation, Nicosia in Honour of Malcolm Wiener, Nicosia, 1998 October 29-30. Vienna: Verlag der Österreichischen Akademie der Wissenschaften; 2001. p. 195-202.

———. Time out: the current impasse in Bronze Age archaeological dating. In: Foster KP, Laffineur R, editors. METRON: measuring the Aegean Bronze Age. Proceedings of the 9th International Aegean Conference, New Haven, Yale University, 2002April 18-21. Aegaeum 24. Liège: Histoire de l'art et archéologie de la Grèce antique; Austin: Program in Aegean Scripts and Prehistory; 2003a. p. 363–99.

———. The absolute chronology of Late Helladic IIIA2 revisited. Annual of the British School at Athens. 2003b;98:239-50.

———. Chronology going forward (with a query about 1525/4 B.C.). In: Czerny E, Hein I, Hunger H, Melman D, Schwab A, editors. Timelines. Studies in honour of Manfred Bietak. Vol. 3. Orientalia Lovaniensia Analecta 149. Leuven: Peeters; 2006a. p. 317-28.

———. Egypt & time. Egypt and the Levant. 2006b;16:325-39.

———. Times change: the current state of the debate in Old World chronology. In: Bietak M, Czerny E, editors. The synchronisation of civilisations in the Eastern Mediterranean in the second millennium B.C. III. Proceedings of the SCIEM 2000-2nd EuroConference, Vienna, 2003 May 28-June 1. Vienna: Verlag der Österreichischen Akademie der Wissenschaften; 2007. p. 25-47.

———. Cold fusion: the uneasy alliance of history and science. In: Manning SW, Bruce MJ, editors. Tree-rings, kings, and Old World archaeology and environment. Papers Presented in Honor of Peter Ian Kuniholm. Oxford: Oxbow; 2009a. p. 277-92.

———. Reply to the papers by Manning et al. and Friedrich et al. In: Manning SW, Bruce MJ, editors. Tree-rings, kings, and Old World archaeology and environment. Papers Presented in Honor of Peter Ian Kuniholm. Oxford: Oxbow; 2009b. p. 317-32.

———. The State of the debate about the date of the Theran eruption. In: Warburton D, editor. Time's up: dating the Minoan eruption of Santorini. Acts of the Minoan Eruption Chronology Workshop, Sandbjerg (November 2007), Aarhus: Aarhus University Press; 2009c. p. 197-206.

Figures

Figure 1. Map of the Aegean.

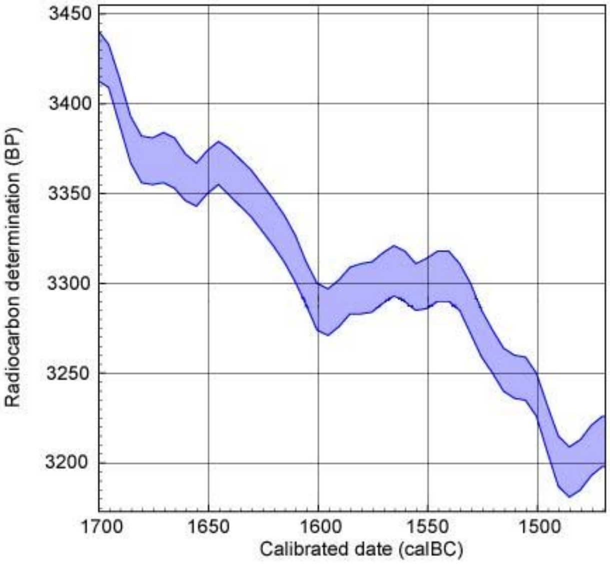

Figure 2. INTCAL09 calibration curve. Detail of the period 1700–1470 BC.

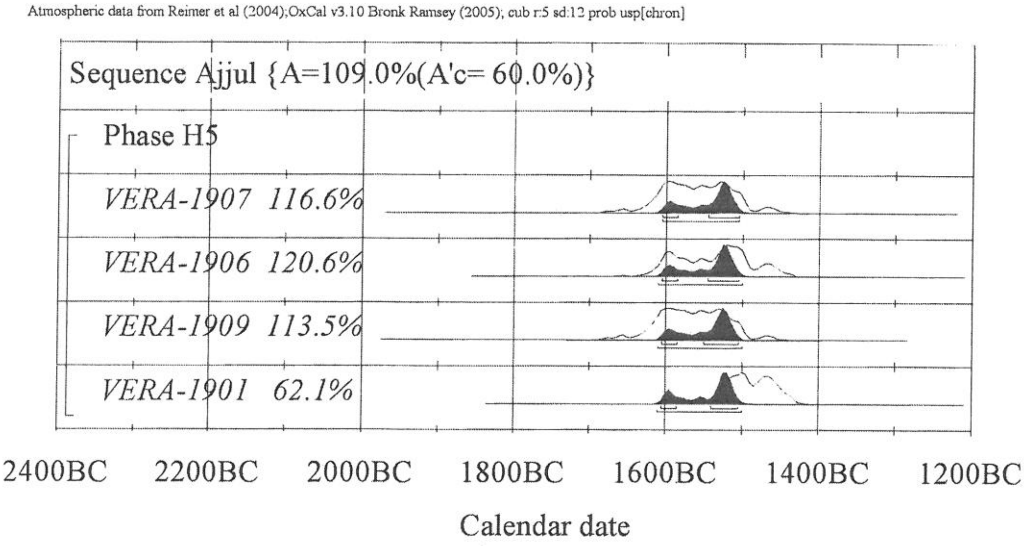

Figure 3. Radiocarbon dates from Stratum H5 at Tell el ‘Ajjul (after Fischer 2009, fig. 4).