COMMENTARY

On the enigma of dating the Minoan eruption of Santorini

Walter Kutschera[a,1]

The Greek island of Santorini (named Thera in ancient times) is located in the Aegean Sea and experienced a massive volcanic eruption some 3,600 y ago (~1600 BCE). Recent geological investigations have concluded that the eruption was even more massive than originally thought (1). This eruption is commonly referred to as the "Minoan" eruption because it happened when the Minoan civilization on the neighboring island Crete was a thriving force in the Aegean and was probably affected by the eruption. The date of the eruption has been debated for many years (2), because it provides an absolute time marker for the Bronze Age in the Eastern Mediterranean. However, no consensus has been reached for this date based on archaeological methods on the one hand and on various scientific approaches on the other hand (e.g., ^{14}C dating, tree-ring studies, and ice core and stalagmite analysis). For quite some time, a difference of about 100 y persisted between the two methods, sometimes called the "high chronology" for an earlier date in the 17th century BCE favored by the scientific methods and a "low chronology" in the 16th century BCE favored by the archaeological methods. This discrepancy has been discussed on many occasions (3–5).

The importance of an exact date for the history of the Eastern Mediterranean has been metaphorically pointed out by Peter M. Warren from the Department of Archaeology and Anthropology of the University of Bristol (ref. 6, p. 305): "Let us imagine that historians at some future date were investigating the political relationship between Germany and the United Kingdom when the forceful Margaret Thatcher was the latter's Prime Minister. Some uncertainty had arisen. Most of the investigators understood Thatcher's relationship was with the equally forceful Chancellor Helmut Kohl, but a smaller school of opinion believed it was with the exceptionally forceful Chancellor Otto von Bismarck, some one hundred years earlier. Of course, we today know it was Thatcher–Kohl, but let us allow a future uncertainty. All would agree that no appropriate historical and political reconstruction could be made unless the chronological relationship was correctly determined. With whom, the hypothetical historians ask, was Margaret Thatcher in (sometimes volcanic) debate?"

This, then, means that one wants to have an accurate and precise date of the eruption, something which has eluded scholars of the Eastern Mediterranean history despite considerable efforts on many different fronts. Concentrating on the ^{14}C dating of the eruption, a key ingredient was the discovery of an olive branch supposedly buried alive by the tephra of the Santorini eruption (7). Although such a subfossil wood was an almost perfect material to determine the date of the eruption by radiocarbon dating, a number of questions have arisen since its discovery. Recently, the formation of reliable tree rings in olive trees was challenged (8), which was a prerequisite to apply "wiggle matching" of the ^{14}C measurements to the ^{14}C calibration curve to obtain a precise date of the eruption (7). In general, an absolute date can be determined from a ^{14}C measurement only with the help of a calibration curve (9) which reflects the natural fluctuations of the ^{14}C content in the atmosphere over time. For the last 13,900 y, this curve was established through ^{14}C measurements in tree-ring series of known age (9). Depending on the shape of the calibration curve at the time of interest, the uncertainty of the calibrated date is often larger than the one of the measured ^{14}C content in the sampled material. A particular difficulty arises for so-called "plateaus" of the calibration curve, which does not allow one to translate a precisely measured ^{14}C content into an equally precise calibrated date. As it happens, such a plateau covers a critical time range for the Santorini eruption, from ~1600 BCE to ~1530 BCE (9). To make things worse, the single-year calibration of Pearson et al. (10) generated another plateau, different from the one of Reimer et al. (9). The situation is depicted in Fig. 1, reproduced from Pearson et al. (10). While the distribution of calibrated ^{14}C dates with 95% probability from the olive tree branch (1627 to 1596 BCE) and an Akrotiri seed assemblage (1646 to 1606 BCE) points to a calendar date before 1600 BCE using the original calibration curve (9), they cover a much larger

[a]Faculty of Physics–Isotope Physics, University of Vienna, 1090 Vienna, Austria

Author contributions: W.K. wrote the paper.

The author declares no competing interest.

See companion article, "Securing timelines in the ancient Mediterranean using multiproxy annual tree-ring data," 10.1073/pnas.1917445117.

[1]Email: walter.kutschera@univie.ac.at.

First published April 14, 2020.

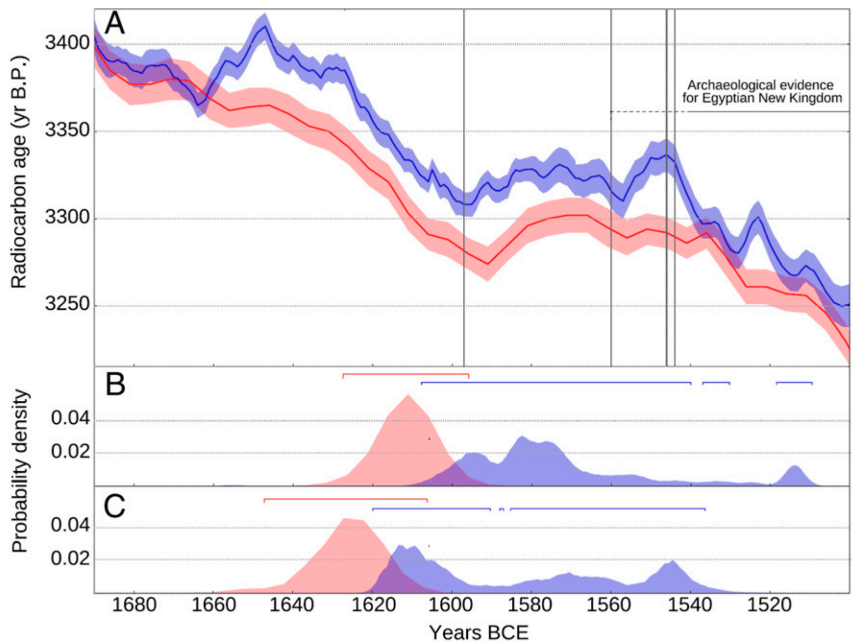

Fig. 1. Demonstration of how the ^{14}C dating of the Minoan eruption of Santorini depends on the magnitude and shape of the ^{14}C calibration curves. The red curve in *A* is the widely used IntCal13 calibration curve (9), based on ^{14}C measurements in a variety of absolutely dated tree-ring series for the time range shown. The blue curve in *A* is the calibration curve (10) based on annual ^{14}C measurements of tree-ring series from North American bristlecone pine and Irish oak. The offset of this curve with respect to IntCal13 considerably changes the time range covered by the two ^{14}C dating results of the olive tree (7) and Akrotiri seeds (5). This is shown by the red and blue probability distributions of the calibrated time ranges for the olive tree in *B* and the Akrotiri seeds in *C*, respectively. The vertical black lines in *A* indicate tree-ring growth anomalies found in bristlecone pines (14), indicating possible volcanic events. The archaeological time range for the eruption is indicated by the horizontal black line (11). Reprinted from ref. 10, which is licensed under CC BY-NC 4.0.

time range with the additional calibration curve (10). In particular, they reach well into the 16th century BCE, closer to an eruption date of ∼1540 BCE favored by archaeologists (11). The consequences of the findings of Pearson et al. (10) were elucidated in a brief comment in *Science* (12).

The publication of Pearson et al. in PNAS (13) goes a step farther by synchronizing a "floating" tree-ring series of the Mediterranean juniper, measured with annual ^{14}C resolution, to the also annually ^{14}C-measured absolute tree-ring series of the North American bristle cone pine and Irish oak (10). This in itself does not solve the radiocarbon dating dilemma and still has to await a generally accepted new ^{14}C calibration curve after IntCal13 (9), but it provides now a Mediterranean tree-ring series with yearly resolution in the critical time period of the Santorini eruption. Pearson et al. (13) performed an X-ray resonance fluorescence analysis of the juniper tree-ring series, which revealed a significant depletion of calcium around 1560 BCE. As the authors point out (13), this was possibly caused by the Santorini eruption. Further analysis of ^{14}C and chemical signatures in the juniper tree-ring series may lead to a firmer date of the Santorini eruption (13). If this date is verified, the long-sought absolute time marker for the chronology of the Bronze Age in the Eastern Mediterranean including Egypt and the Levant has finally been found. This, then, would allow archaeologists and historians to fine-tune the interactions of ancient civilizations during this time period.

In conclusion, however, one should realize that so far all efforts to date the Santorini eruption depend on indirect methods, i.e., on dating material which records in different ways the effect of the eruption. Notwithstanding the uncertainties of the particular dating method, i.e., ^{14}C dating (10, 13), tree-ring dating (3, 14), ice-core stratigraphy (3), and stalagmite dating (15), an eruption date established with these methods will depend on correctly linking the observed signal to the Santorini eruption. In a similar way, archaeological dating depends on linking characteristic artifacts from supposedly well-established chronologies in the Eastern Mediterranean (e.g., through the historical chronology of ancient Egypt) to similar artifacts buried in the tephra of the eruption on Santorini. Sometimes links to the eruption are also established by finding traces of tephra characteristic of the Santorini eruption in deposits of neighboring "well-dated" archaeological sites.

The most direct method to determine the date of the Santorini eruption would be the dating of the ejected material (tephra) itself. With such a method the historical date of 79 CE for the eruption of Vesuvius in Italy was successfully verified by $^{40}Ar/^{39}Ar$ dating of the mineral sanidine in the tephra of Vesuvius (16, 17). This clearly was a tour de force because the long half-life of ^{40}K (1.25×10^9 y) resulted in a very low radiogenic ^{40}Ar signal accumulated since the relatively recent time of the eruption, when the K-Ar clock was set to zero. Considering the improvement of the $^{40}Ar/^{39}Ar$ dating method since then and the older age of the Minoan eruption of Santorini, it may indeed be possible to date it with this method, provided that one finds the proper potassium-rich mineral (sanidine) in the ejecta of the Santorini eruption. Because of the long half-life of ^{40}K, it is unlikely that one would arrive at a very precise date, but the accuracy may be better than that of any of the indirect dating methods. The challenge, though, is to find the proper material in the tephra of Santorini. It is possible that one has to work through tons of tephra to find it. If such a project is performed, it may help to bring the enigma of dating the Minoan eruption of Santorini a little closer to a solution.

Acknowledgments

I acknowledge helpful discussion on the manuscript with Eva Maria Wild.

1 H. Sigurdsson *et al*., Marine investigations of Greece's Santorini volcanic field. *Eos (Wash. D.C.)* **87**, 337–342 (2006).
2 M. L. Aitken *et al*., The Thera eruption: Continuing discussion of the dating. *Archaeometry* **30**, 165–182 (1988).
3 M. G. L. Baillie, Volcanoes, ice-cores and tree-rings: One story or two? *Antiquity* **84**, 202–215 (2010).
4 P. Cherubini *et al*., Bronze Age catastrophe and modern controversy: Dating the Santorini eruption. *Antiquity* **88**, 267–291 (2014).
5 S. W. Manning *et al*., Dating the Thera (Santorini) eruption: Archaeological and scientific evidence supporting a high chronology. *Antiquity* **88**, 1164–1179 (2014).
6 P. M. Warren, "The date of the Thera eruption in relation to Aegean-Egyptian interconnections and the Egyptian historical chronology" in *Timelines: Studies in Honour of Manfred Bietak, Orientalia Lovaniensia Analecta 149*, E. Czerny, I. Hein, H. Hunger, D. Melman, A. Schwab, Eds. (Peeters, Leuven, Belgium, 2006), vol. II, pp. 305–321.
7 W. L. Friedrich *et al*., Santorini eruption radiocarbon dated to 1627-1600 B.C. *Science* **312**, 548 (2006).
8 Y. Ehrlich, L. Regev, E. Boaretto, Radiocarbon analysis of modern olive wood raises doubts concerning a crucial piece of evidence in dating the Santorini eruption. *Sci. Rep.* **8**, 11841 (2018).
9 P. J. Reimer *et al*., IntCal13 and Marine13 radiocarbon age calibration curves 0– 50,000 years cal BP. *Radiocarbon* **55**, 1869–1887 (2013).
10 C. L. Pearson *et al*., Annual radiocarbon record indicates 16th century BCE date for the Thera eruption. *Sci. Adv.* **4**, r8241 (2018).
11 M. Bietak, Radiocarbon and the date of the Thera eruption. *Antiquity* **88**, 277–282 (2014).
12 L. Wade, Study reignites debate about when Thera blew its top. *Science* **361**, 634 (2018).
13 C. Pearson *et al*., Securing timelines in the ancient Mediterranean using multiproxy annual tree-ring data. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 8410–8415 (2020).
14 M. W. Salzer, M. K. Hughes, Bristlecone pine tree rings and volcanic eruptions over the last 5000 yr. *Quat. Res.* **67**, 57–68 (2007).
15 S. Badertscher *et al*., Speleothems as sensitive recorders of volcanic eruptions – the Bronze Age Minoan eruption recorded in a stalagmite from Turkey. *Earth Planet. Sci. Lett.* **392**, 58–66 (2014).
16 P. Renne *et al*., $^{40}Ar/^{39}Ar$ dating into the historical realm: Calibration against Pliny the Younger. *Science* **277**, 1279–1280 (1997).
17 M. Lanphere *et al*., $^{40}Ar/^{39}Ar$ ages of the AD 79 eruption of Vesuvius, Italy. *Bull. Volcanol*. **69**, 259–263 (2007).