Radiocarbon, Vol 65, Nr 3, 2023, p 681–691 DOI:10.1017/RDC.2023.35
© The Author(s), 2023. Published by Cambridge University Press for the Arizona Board of Regents on behalf of the University of Arizona. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

CALIBRATION OF MULTIPLE TREE-RING BLOCKS AND ITS IMPLICATION ON THE DEBATE OF MINOAN ERUPTION OF SANTORINI AROUND 17TH–16TH CENTURY BCE

Harsh Raj* • Lior Regev • Elisabetta Boaretto

D-REAMS Radiocarbon Laboratory, Scientific Archaeology Unit, Weizmann Institute of Science, Rehovot, Israel

ABSTRACT. The Minoan eruption of Santorini, Greece, is an important and often-debated chronological marker in contexts of the Eastern Mediterranean region. Among various age estimates of this event, one based on wiggle-matching of radiocarbon (^{14}C) dates from an olive branch found in Santorini by Friedrich et al. (2006) has been widely discussed. Calibrated age estimates based on wiggle-matching of these ^{14}C ages have been changing with improvements in the ^{14}C calibration curve. As also shown earlier, calibration of average ^{14}C age of multiple tree rings dated together should not be done using a single-year calibration curve. Since recent calibration curves include many single-year ^{14}C datasets, a different approach should be considered to calibrate the average ^{14}C age of block of multiple tree rings. Here we have demonstrated the use of multiple moving average (MA) calibration curves for calibrating the sequence of four ^{14}C ages reported for the Santorini olive branch. The resultant calibrated ages for the Minoan Eruption are relatively younger than previous estimates and range from the late-17th century BCE to mid-16th century BCE date.

KEYWORDS: calibration, IntCal20, Minoan Eruption, radiocarbon dating, tree rings.

INTRODUCTION

The Minoan eruption of Santorini (Thera), Greece, is an important and often-debated chronological marker in the contexts of the Eastern Mediterranean region. A significant number of investigations have been carried out to constrain the age of the Minoan eruption of Santorini (Warren 1984; Hammer et al. 1987; Bronk Ramsey et al. 2004; Friedrich et al. 2006; Warburton 2009; Manning and Kromer 2012; Manning et al. 2014; Pearson et al. 2018; Ehrlich et al. 2021). Still, a long outstanding issue of inconsistency between the archaeological and radiometric age estimates of this significant volcanic event remains. Among various estimates, one based on the radiocarbon (^{14}C)-dated olive branch from Santorini (Thera) reported by Friedrich et al. (2006) has been widely discussed mainly for two reasons. Firstly, Friedrich et al. (2006) provided the most precise and direct date of the Minoan eruption using the wiggle-matching technique on ^{14}C ages from the olive tree branch (Heinemeier et al. 2009). Using the IntCal04 calibration curve, the authors determined the final calibrated age range of the event to 1627–1600 BCE (1613 ± 13 BCE) for a 95% confidence interval. Secondly, this ^{14}C-based estimate still disagreed with archaeological evidences, which places the Minoan eruption in the 16th century BCE (Friedrich et al. 2006).

Friedrich et al. (2006) carried out wiggle-matching, relying on ring counting of an olive branch that they found buried in the pumice of the eruption. They sampled it in four sections or blocks, each containing multiple rings. The authors reported 13 (±3), 24 (±5), 22 (±5), and 13 (±3) rings, respectively, for the four sections, and the ^{14}C age of these four sections were 3383 (±11), 3372 (±12), 3349 (±12), and 3331 (±10) yr BP, respectively. Cherubini et al. (2014) debated the identification of olive tree rings and suspected the reliability of the age estimate by Friedrich et al. (2006). However, Friedrich et al. (2014) showed that even without the constraints from ring counting,

*Corresponding author. Email: harsh.raj@weizmann.ac.il

using a simple ordered sequence, the age of the outermost section ranged between 1656–1609 BCE. Recent work by Ehrlich et al. (2018, 2021) on annual growth in modern olive trees supported the Santorini branch age. However, the chronological anomalies observed in their study could place the age of the Minoan eruption of Santorini in the mid-16th century BCE.

Apart from the ring counting, the ^{14}C calibration curve plays a crucial role in determining the calibrated age. The shape of the calibration curve also affects the precision associated with the calibrated ages. Pearson et al. (2018) demonstrated that during the concerned time period, single year tree-ring ^{14}C records from California (Bristlecone Pine) and Ireland (Oak) showed a clear offset with respect to IntCal13 values. The authors suggested that this offset could shift the calibrated age range of the Minoan eruption towards the 16th century BCE. Another set of single year tree-ring ^{14}C measurements by Friedrich et al. (2020) conformed with the offset observed by Pearson et al. (2018), increasing the possibility of the calibration of the Minoan eruption date to the 16th century BCE. These observations underline the importance of the calibration curve for dating this important volcanic event. The most recent ^{14}C calibration curve (IntCal20; Reimer et al. 2020) includes these single year tree-ring ^{14}C records, which influence the calibration of Minoan Eruption's ^{14}C dates.

These previous investigations on annual olive growth and calibration data around the 17th–15th century BCE have certainly improved our understanding of the accuracy of calibrated age of the Santorini olive branch, whose last ring supposedly represents the age of the Minoan Eruption in Santorini. However, the ^{14}C-based dates are still at odds with some archaeological age estimates.

It is noticeable that Friedrich et al. (2006) sampled the olive branch in four sections or blocks, each containing multiple tree rings. Therefore, the ^{14}C age estimate of every olive section or block is essentially the average of the ^{14}C ages of all the rings (or corresponding calendar years) in the respective section. Calibrating an average ^{14}C age of multiple calendar years on a highly resolved (single year) calibration curve might not yield the correct calibrated age range of the sample. The blocked nature of some ^{14}C dates had already been identified and discussed in earlier literature, as initial calibration curves usually consisted of samples formed over multiple years (Stuiver 1993). Blocked nature of such ^{14}C datasets have also been taken into consideration in building recent calibration curves (Heaton et al. 2009; Niu et al. 2013; Heaton et al. 2020). However, the current calibration curve (IntCal20) include many annual tree-ring records (Heaton et al. 2020). Stuiver (1993) had shown that samples growing over multiple years when calibrated on moving average curve produced smaller calendar age ranges compared to age ranges obtained using highly resolved (single year) calibration curve. So, it is crucial to look at the time resolution of the calibration curve before calibrating the average ^{14}C age of a block of multiple tree rings. The most recent ^{14}C calibration curve consists of many annually resolved ^{14}C datasets around the 17th–15th century BCE (Reimer et al. 2020), and it suggests that a simple calibration of the Santorini olive branch ^{14}C ages might not be a good choice. Thus, a more appropriate calibration method for average ^{14}C age needs to be adopted. In this study, a new approach for the calibration of average ^{14}C ages of multiple tree rings has been applied, and its implication on the Minoan Eruption age has been discussed.

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

METHODS

IntCal04 (Reimer et al. 2004) calibration curve was used by Friedrich et al. (2006) to estimate the age of the olive branch found in the volcanic debris of the Minoan eruption. Since then, there have been many improvements in the ^{14}C calibration curve, resulting in the most recent IntCal20 calibration curve (Heaton et al. 2020; Reimer et al. 2020). It is deemed necessary to re-calibrate the ^{14}C ages on a recent and updated calibration curve, as they include more datasets and better represent past atmospheric ^{14}C levels. The dataset of IntCal20 calibration for the time period between 1700–1500 BCE is fairly dense, with 13 different records (Reimer et al. 2020). These records include annually resolved datasets along with some temporally less resolved records.

Each olive section analyzed by Friedrich et al. (2006) consisted of multiple tree rings. So, each consecutive set of tree rings corresponds to a consecutive set of calendar years. As interannual ^{14}C levels can vary significantly, the ^{14}C age of one section should be better represented by the average ^{14}C age of consecutive calendar years indicated by the number of rings in that section, rather than the ^{14}C age of one (middle) calendar year of the section. Therefore, calibration of the average ^{14}C age of multiple calendar years on a curve consisting of average ^{14}C values of the same number of consecutive calendar years seems like the more appropriate method. It has already been demonstrated earlier by Stuiver (1993). CALIB (Stuiver and Reimer 1993) program does allow users to smoothen the calibration curve with a moving average, but currently it does not have option to use multiple MA curves in a sequence for calibration. Therefore, simple MA curves were constructed for this study. Moving average (MA) curves were created using annual tree-ring records between 1700–1500 BCE, the period concerning the Minoan Eruption. Based on the reported number of tree rings in the olive sections (Friedrich et al. 2006), different MA curves with moving average values were created (Table S1). The following formula was used to calculate moving average values to construct the MA curve,

$$A_x = \frac{\sum_{i=(x+n-1)}^{x} a_i}{n} \tag{1}$$

Here A_x is the average ^{14}C age value corresponding to the "x" calendar year in cal yr BP unit, n is the number of years averaged (or the number of rings in the wood section), and a_i is the annual ^{14}C age value of each calendar year from the IntCal20 dataset. Based on the above formula, a calendar year range will be represented by the last ring (year) of a wood section on the MA calibration curve instead of the middle ring (year) of a wood section. To estimate the error or spread in the MA curve, the following formula was used based on error propagation,

$$\sigma_x = \frac{\sqrt{\sum_{i=(x+n-1)}^{x} \left(\sigma_{a_i}\right)^2}}{n} \tag{2}$$

Here σ_x is the error in the calculated A_x value, and σ_{ai} is the error associated with each a_i value from the IntCal20 dataset. $3\sigma_x$ values were used to create each MA curve as 3σ represents 99.7% of possible values. Figure 1 shows a 24-yr MA curve created for this study between 1700–1500 BCE, along with the IntCal20 calibration curve. It can be noted that the wiggles in the MA calibration curve smoothen relatively, suggesting that the MA calibration curve should yield a different probability distribution of the calendar years than a usual IntCal20

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

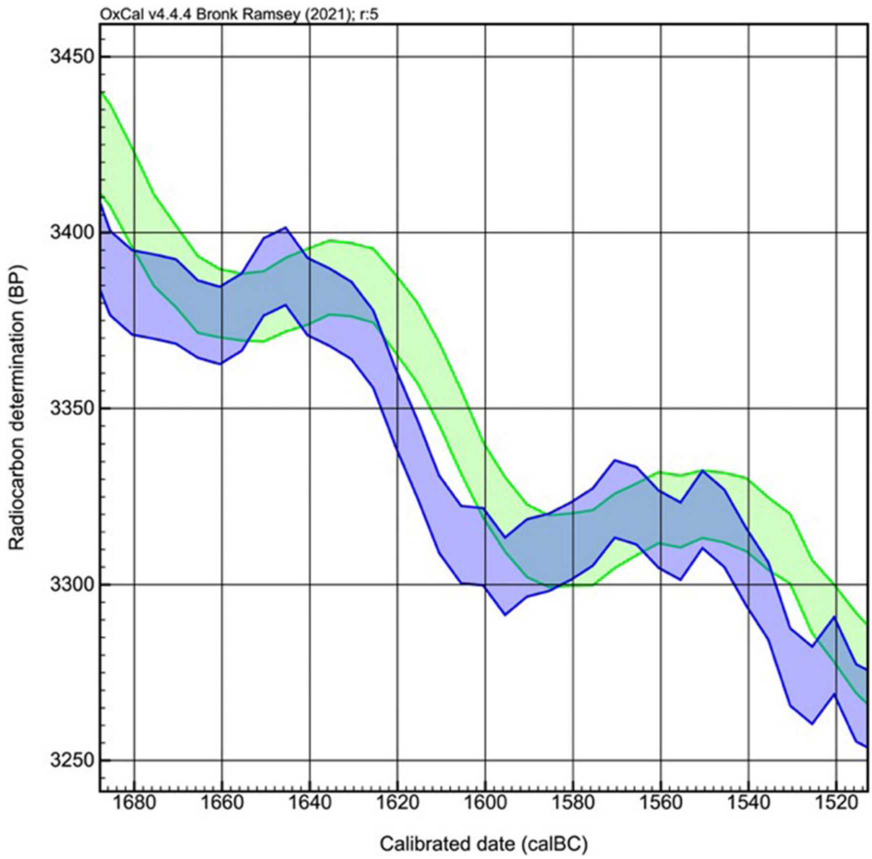

Figure 1 IntCal20 calibration curve (blue) along with 24-yr moving average curve (green) for the time period between 1700 and 1500 BCE. (Please see online version for color figures.)

calibration curve. It is important to note that the above formula is a very simplistic way of constructing MA curve and it does not consider additional uncertainties arising due to laboratory offsets or under-reporting of uncertainty calibration datasets.

RESULTS AND DISCUSSION

Validating MA Curve Calibration

Before applying the MA curve calibration on the olive branch ^{14}C dates, validating the MA calibration curve method is necessary. For this purpose, a dendrochronologically dated *Quercus* sp. ^{14}C record (69, 53) reported by Pearson et al. (2020) was used. This annual ^{14}C tree-ring record spans between 1679 BCE and 1551 BCE. Four consecutive sections of 13, 24, 22, and 13 yr starting from 1679 BCE were selected from the *Quercus* sp. ^{14}C record to apply the same wiggle-matching model as that will be applied on the Santorini olive branch ^{14}C dates. The average ^{14}C age of these four sections is calculated to be 3383 (±11), 3381 (±11), 3370 (±14), and 3320 (±21), respectively.

Now, two wiggle-matching models, first considering ring counts as accurate and second considering only the sequence of the ^{14}C ages, were applied to these four ^{14}C ages obtained

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

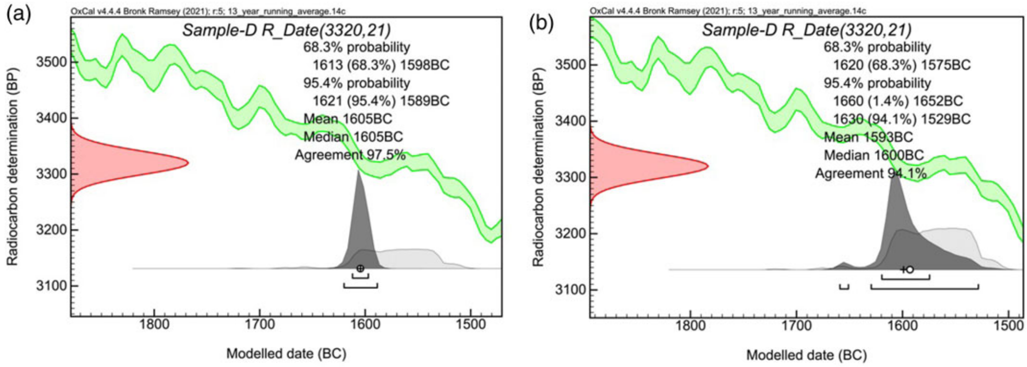

Figure 2 Calibration results for *Quercus* sp. ^{14}C record between 1679 and 1607 BCE (Pearson et al. 2020) using MA curves (green) (a) when accurate ring count is considered and (b) when only sequence of ^{14}C dates is considered. The circle represents the mean and the cross represents the median.

from the *Quercus* sp. record (Table S2). The MA calibration curve method includes the use of multiple curves depending on the ring counts in every section. In the current example, three different MA curves have been used in the model based on ring counts. Based on simple ring counting, the last ring in each model should correspond to 1607 BCE. The first OxCal model with accurate ring count yields calibrated age of the last ring to be about 1605 (±8) BCE and 1605 (±16) BCE, for 68.3% and 95.4% confidence intervals, respectively (Figure 2a), which is in very good agreement with its true dendrochronological age. The second OxCal model, which considers only the sequence of ^{14}C dates, yields 68.3% and 95.4% probability range of calibrated age that also includes 1607 BCE, the true age of the last ring (Figure 2b). These results show that the MA curve calibration method does yield accurate calendar ages and thus can be applied on multiple tree rings ^{14}C dates.

Another validation is done by comparing the calibration result of a single ^{14}C date obtained using CALIB program and using an MA curve constructed in this study. The ^{14}C age of last section of Santorini Olive branch (3310 ± 10 yr BP) is calibrated using a smoothed IntCal20 curve with moving average of 13 yr (Figure S1a) and also using 13-yr MA curve constructed in this study (Figure S1b). It is observed that both MA curves (Figure S1a and S1b) appear similar and the resultant calendar age range is also similar. The CALIB program gives age ranges of 1620–1607 and 1578–1546 BCE for 68.3% probability, and an age range of 1623–1541 BCE for 95.4% probability. The MA curve created in this study gives age range of 1613–1601 and 1575–1538 BCE for 68.3% probability, and an age range of 1617–1534 BCE for 95.4% probability. This result is similar to CALIB result but there is a slight shift towards younger ages, which is due to Equation (1) providing the calendar age of the last ring in a block. The similarity between these two results demonstrates that the MA curves constructed in this study can be used to calibrate sequence of Santorini olive branch ^{14}C dates.

Olive Branch Calibration

The use of a simple moving average curve for calibration assumes that each tree ring in the concerned wood section contributes equally to the average ^{14}C value of the section. In other words, each tree ring gets equal weightage. For simplicity, this assumption is considered in this study. First of all, the ^{14}C date of only the last section of the olive branch was calibrated using the MA curve. As per Friedrich et al. (2006), the last section

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

had about 13 tree rings, so a 13-yr moving average curve was used to calibrate the last section's ^{14}C date. The calibrated age's 95.4% probability range spans between 1617 BCE and 1534 BCE (Figure S1b), suggesting the late-17th century BCE until the mid-16th century BCE as a possible age range for the event. The obtained calendar age range of around 83 yr can be reduced by using the wiggle-matching technique, which provides a more precise age value. Thus, different wiggle-matching models based on sequence and gap information on the ^{14}C ages of the olive branch sections were run on OxCal4.4 (Bronk Ramsey 2001) to obtain a much more precisely calibrated age range for the last section. For comparison, same models were also run using IntCal13 and IntCal20 curves. The model scenarios and OxCal results are listed in Table 1.

The first model assumes that the ring counts reported by Friedrich et al. (2006) for the olive branch are accurate. This model (#1 in Table 1) gives age range between 1616–1578 BCE (95.4% confidence). When compared with IntCal13 and IntCal20 results, the MA calibration results are slightly younger. It should also be mentioned that IntCal20 calibration yields a bimodal probability distribution of calendar age, as also reported by van der Plicht et al. (2020). However, the MA calibration provided a unimodal probability distribution for the same age. The second model (#2 in Table 1) considers a 25% increment in ring count and an error of 25% of the section count. Different MA calibration curves (moving average window increased by 25%) have been used according to the number of ring counts considered in the model of the MA curve (Table S3). The resulting calibrated age range between 1612–1567 BCE (95.4% confidence) is also younger than the IntCal13 and IntCal20 results. The third model (#3 in Table 1) considers only a sequence of four ^{14}C dates of olive branch sections (Figure 3). Applying a MA curve considers the information of ring count in a section, but the model doesn't use any gap information between ^{14}C dates. The calibrated age range obtained from this model spans between 1618–1541 BCE (95.4% confidence). The 68.3% confidence interval span between 1616–1587 BCE (54.7% confidence) and 1575–1559 BCE (13.6% confidence). It is noticeable that both age ranges in the 68.3% confidence interval include a 16th century BCE age, unlike IntCal13 and IntCal20 results. The fourth model (#4 in Table 1) also uses only a sequence of ^{14}C ages, but with a constant age offset in ^{14}C ages. Manning et al. (2020) suspected an offset of about 5–8 ^{14}C yr in the 1600–1540 BCE interval and tried to see the influence of this offset on Thera ^{14}C age calibration. The same 8 ^{14}C yr offset has been incorporated in the fourth model. The resulting calibrated age range from the MA curve calibration method spans between 1614–1538 BCE (95.4% confidence).

It is clearly observed that the calibration results of all models using the MA curve are younger than the results obtained using IntCal13 or IntCal20. A simple sequence model of dates without gap information using IntCal20 or IntCal13 yields calendar age representing the middle ring of the last wood section but not the last ring. But calibration based on the MA curve, which is constructed using Equation (1), yields the calendar age of the last (youngest) ring of the last (youngest) section. It could be one of the reasons behind the younger calendar ages obtained using the MA curve method. As the MA curve results are better representative of the last ring age, it indicates that the new MA curve approach provides more accurate age estimates, especially in cases where the number of ring counts can be ambiguous. In cases with ambiguity in the ring counts of a tree section one can still use the information of presence of multiple rings in the section. In such scenario, a safe estimate can be used to choose a MA curve, which can provide more accurate calibrated age value than a simple calibration curve.

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

Table 1 Scenarios for calibration of olive branch ^{14}C ages (Friedrich et al. 2006) and calibrated age range (BCE) of the outermost section of the branch.

Model No.	Model description	IntCal13 curve (68.3% probability) (95.4% probability)	IntCal20 curve (68.3% probability) (95.4% probability)	*Moving average curve (68.3% probability) (95.4% probability)
1.	Ring counts given by Friedrich et al. (2006) are accurate	1621–1608 (68.3%) **1626–1603 (95.4%)**	1611–1592 (68.3%) **1618–1582 (95.4%)**	1609–1591 (68.3%) **1616–1578 (95.4%)**
2.	Ring counts are increased by 25%, and gap uncertainty is set at 25% of the count	1626–1612 (68.3%) **1634–1607 (95.4%)**	1616–1591 (68.3%) **1622–1575 (95.4%)**	1604–1582 (68.3%) **1612–1567 (95.4%)**
3.	Only sequence of olive sections is considered	1647–1625 (68.3%) **1662–1621 (95.4%)**	1625–1600 (62.5%) 1574–1567 (5.8%) **1626–1546 (95.4%)**	1616–1587 (54.5%) 1575–1559 (13.8%) **1618–1541 (95.4%)**
4.	Only sequence of olive sections is considered with 8 ^{14}C yr offset (Manning et al. 2020)	1629–1612 (68.3%) **1641–1603 (90.4%)** **1582–1563 (5.0%)**	1621–1596 (62.5%) 1584–1563 (5.8%) **1622–1546 (95.4%)**	1612–1569 (68.3%) **1614–1538 (95.4%)**

*The MA results are based on only the single-year datasets included in IntCal20.

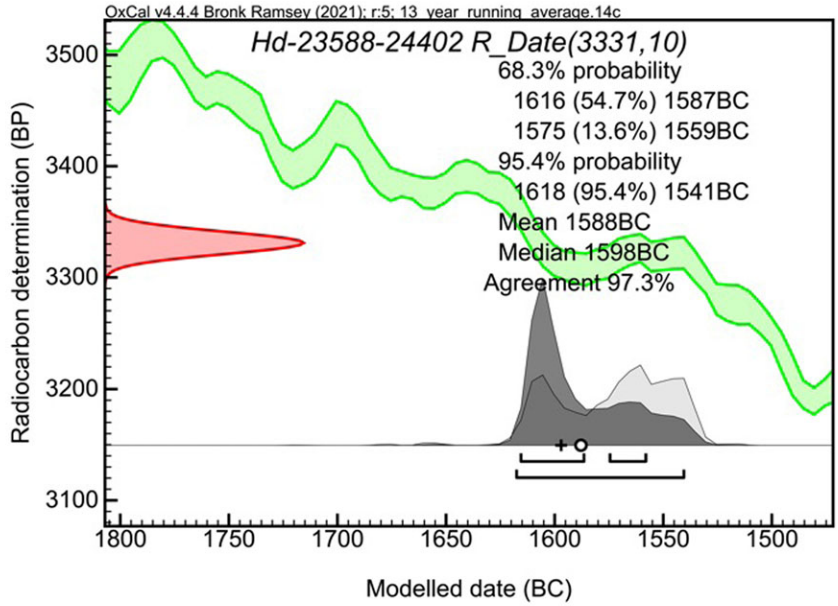

Figure 3 Calibration result of olive branch ^{14}C dates when only the sequence of the olive section is considered (model 3). The circle represents the mean and the cross represents the median.

Considering all four model results from the MA curve method, the olive branch's oldest possible age is about 1618 BCE, which also agrees well with the calibration result of only the last olive section (Figure S1b). The olive branch's youngest possible age is 1541 BCE without an offset and 1538 BCE with an offset of 8 ^{14}C yr. It is observed that an offset of 8 ^{14}C yr results in calendar years being slightly younger, and also, the probability of a 16th century BCE date increases. The increase in the probability of 16th century BCE dates is observed in all four models when the MA curve method is used.

While estimating the possible date of the Minoan eruption of Santorini, the resultant calendar age from the olive branch (Friedrich et al. 2006) should not be seen in isolation. Age estimate based on other plant remains (short-lived) from the Akrotiri volcanic destruction level (VDL) should also be considered. An average ^{14}C age of 3350 (±10) BP years has been derived for the Minoan Eruption based on short-lived plant materials (Bronk Ramsey et al. 2004; Manning et al. 2020; van der Plicht et al. 2020). Since this estimate is based on short-lived material, it should be calibrated on a standard IntCal20 curve but not on MA curve. Based on the IntCal20 curve calibration, the resulting calendar age spans between 1732 and 1544 BCE (95.4% confidence) with multi-modal probability distribution (Figure S2a). For 68.3% confidence interval highest probability lies between 1636 and 1612 BCE (48.5%), and for 95.4% confidence interval, the highest probability lies between 1645 and 1607 BCE (54.7%). Nevertheless, the probability for a 16th century BCE date also exists in the calendar age result.

Based on the olive branch age calibration, it is understood that any calendar age older than 1618 BCE is very improbable. It is noted that models for olive branch dates using ring counts (models #1 and #2) yield an age range that is compatible with the age range of

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

VDL short-lived plant remains, only in 95.4% confidence interval but not in 68.3% confidence interval. However, models using only a sequence of olive branch dates (models #3 and #4) give an age range compatible with the age range of VDL short-lived plant remains in both 68.3% and 95.4% confidence intervals. This indicates that the ring counts provided for the olive branch probably yield inaccurate age of the event. The inaccuracy associated with olive ring counts has also been demonstrated by Ehrlich et al. (2018, 2021). Therefore, it is better to use models based only on the sequence of dates in this case. When results of models 3 and age range of VDL short-lived plant remains are compared, the overlap occurs between 1616–1612 BCE and 1575–1565 BCE for 68.3% confidence interval. For 95.4% confidence interval the overlap occurs between 1618–1607 BCE and 1581–1544 BCE. Similarly calibrated age range of VDL short-lived plant remains with an 8-yr offset (Figure S2b) when compared with model 4 results, the overlap occurs between 1612–1608 BCE and 1577–1569 BCE for 68.3% confidence interval. For 95.4% confidence interval the overlap occurs between 1614–1540 BCE. Considering the olive branch and VDL short-lived plant remains represent the same event i.e., the Minoan eruption of Santorini (Thera), the event date can be constrained between late 17th century BCE and mid-16th century BCE. The ^{14}C dates from the olive branch and short-lived materials from VDL also indicate that a 15th century BCE age for this volcanic event is very improbable. Synchronism of archaeological evidence between the Egypt, Aegean, and Levant put the Minoan eruption of Santorini after the beginning of the New Kingdom in Egypt (Höflmayer, 2012). ^{14}C records show that the New Kingdom started between 1570–1544 BCE (Ramsey et al. 2010). This age range is included in overlapping age range of olive branch and VDL short-lived plant remains. Considering these three evidence together, a mid-16th century BCE date for the Minoan Eruption appears more probable. However, the debate on Minoan eruption on Santorini stays alive as calibrated age range of olive branch and short-lived plant remains still spans in both 17th and 16th century BCE. We suggest that a more detailed and dense sampling and ^{14}C analysis in many sites with sequence of layers including the Santorini eruption might be a solution for this time enigma.

This study applied the MA curves for calibration to refine the ^{14}C age estimate of the Minoan Eruption based on olive branch section dates. It has been demonstrated here that the calibration using MA curves provides more accurate calibration results. Therefore, this type of approach should be used for calibrating ^{14}C ages of tree blocks or sections consisting of multiple rings. Finally, more ^{14}C dates from samples representing the Minoan eruption are required to refine further the calendar date estimate of the Minoan Eruption of Santorini.

SUMMARY

The average ^{14}C value of multiple tree rings represents the mean of multiple calendar years' ^{14}C values. Thus, calibration of the average ^{14}C value of multiple tree rings on an annually resolved calibration curve may not yield accurate dates. A calibration based on multiple moving average curves has been suggested to calibrate the average ^{14}C values of blocks of multiple tree rings. This method has been validated using a known age tree ^{14}C record. Applying this method to the reported ^{14}C dates of olive branch sections from Santorini shows that the resultant calendar ages are slightly younger than previously observed. The olive branch calibrated age ranges between the late 17th century BCE and mid-16th century BCE.

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2023.35

ACKNOWLEDGMENTS

Authors would like to thank Prof. Charlotte Pearson for input and suggestions. The ^{14}C research was supported by the Exilarch Foundation for the Dangoor Research Accelerator Mass Spectrometer (D-REAMS) Laboratory. H.R. received his fellowship from the Kimmel Center for Archaeological Science. E.B. is the incumbent of the Dangoor Professorial Chair of Archaeological Sciences at the Weizmann Institute of Science.

REFERENCES

Bronk Ramsey C. 2001. Development of the Radiocarbon Calibration Program. Radiocarbon 43(2A):355–363. doi: 10.1017/S0033822200038212

Bronk Ramsey C, Manning SW, Galimberti M. 2004. Dating the volcanic eruption at Thera. Radiocarbon 46(1):325–344. doi: 10.1017/S0033822200039631

Cherubini, P, Humbel, T, Beeckman, H, Gärtner, H, Mannes, D, Pearson, C, Schoch, W, Tognetti, R, Lev-Yadun, S. 2014. The olive-branch dating of the Santorini eruption. Antiquity 88(339):267–273. doi: 10.1017/S0003598X00050365

Ehrlich Y, Regev L, Boaretto E. 2018. Radiocarbon analysis of modern olive wood raises doubts concerning a crucial piece of evidence in dating the Santorini eruption. Scientific Reports 8(1):1–8.

Ehrlich Y, Regev L, Boaretto E. 2021. Discovery of annual growth in a modern olive branch based on carbon isotopes and implications for the Bronze Age volcanic eruption of Santorini. Scientific Reports 11(1):1–11.

Friedrich WL, Kromer B, Friedrich M, Heinemeier J, Pfeiffer T, Talamo S. 2006. Santorini Eruption Radiocarbon Dated to 1627–1600 B.C. Science 312(5773):548. doi: 10.1126/science.1125087

Friedrich WL, Kromer B, Friedrich M, Heinemeier J, Pfeiffer T, Talamo S. 2014. The olive branch chronology stands irrespective of tree-ring counting. Antiquity 88(339):274–277. doi: 10.1017/S0003598X00050377

Friedrich R, Kromer B, Wacker L, Olsen J, Remmele S, Lindauer S, Land A, Pearson C. 2020. A new annual ^{14}C dataset for calibrating the Thera eruption. Radiocarbon 62(4):953–961.

Hammer CU, Clausen HB, Friedrich WL, Tauber H. 1987. The Minoan eruption of Santorini in Greece dated to 1645 BC? Nature (London) 328(6130):517–519. doi:10.1038/328517a0

Heaton TJ, Blaauw M, Blackwell PG, Ramsey CB, Reimer PJ, Scott EM. 2020. The IntCal20 approach to radiocarbon calibration curve construction: a new methodology using Bayesian splines and errors-in-variables. Radiocarbon 62(4):821–863.

Heaton TJ, Blackwell PG, Buck CE. 2009. A Bayesian approach to the estimation of radiocarbon calibration curves: the IntCal09 methodology. Radiocarbon 51(4):1151–1164.

Heinemeier J, Friedrich WL, Kromer B, Ramsey CB. 2009. The Minoan eruption of Santorini radiocarbon dated by an olive tree buried by the eruption. In: Warburton DA, editor. Time's up! Dating the Minoan eruption of Santorini: acts of the Minoan Eruption Chronology Workshop, Sandbjerg, November 2007. Monographs of the Danish Institute at Athens (MoDIA). p. 285–293.

Höflmayer F. 2012. The date of the Minoan Santorini eruption: quantifying the "offset". Radiocarbon 54(3–4):435–448.

Manning SW, Höflmayer F, Moeller N, Dee MW, Ramsey CB, Fleitmann D, Higham T, Kutschera W, Wild EM. 2014. Dating the Thera (Santorini) eruption: archaeological and scientific evidence supporting a high chronology. Antiquity 88(342):1164–1179. doi: 10.1017/S0003598X00115388

Manning SW, Kromer B. 2012. Considerations of the scale of radiocarbon offsets in the east Mediterranean, and considering a case for the latest (most recent) likely date for the Santorini eruption. Radiocarbon 54(3–4):449–474.

Manning SW, Wacker L, Büntgen U, Bronk Ramsey C, Dee MW, Kromer B, Lorentzen B, Tegel W. 2020. Radiocarbon offsets and old world chronology as relevant to Mesopotamia, Egypt, Anatolia and Thera (Santorini). Scientific Reports 10(1):1–14.

Niu M, Heaton TJ, Blackwell PG, Buck CE. 2013. The Bayesian approach to radiocarbon calibration curve estimation: the IntCal13, Marine13, and SHCal13 methodologies. Radiocarbon 55(4):1905–1922.

Pearson C, Wacker L, Bayliss A, Brown D, Salzer M, Brewer P, Bollhalder S, Boswijk G, Hodgins G.

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press

2020. Annual variation in atmospheric ^{14}C between 1700 BC and 1480 BC. Radiocarbon 62(4):939–952.

Pearson CL, Brewer PW, Brown D, Heaton TJ, Hodgins GW, Jull AT, Lange T, Salzer MW. 2018. Annual radiocarbon record indicates 16th century BCE date for the Thera eruption. Science Advances 4(8):p.eaar8241.

Ramsey CB, Dee MW, Rowland JM, Higham TF, Harris SA, Brock F, Quiles A, Wild EM, Marcus ES, Shortland AJ. 2010. Radiocarbon-based chronology for dynastic Egypt. Science 328(5985):1554–1557.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck PG, Burr GS, Cutler KB, Damon PE, et al. 2004. Intcal04: terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46(3):1029–1058.

Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Ramsey CB, Butzin M, Cheng H, Edwards RL, Friedrich M, et al. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4): 725–757.

Stuiver M. 1993. A note on single-year calibration of the radiocarbon time scale, AD 1510–1954. Radiocarbon 35(1):67–72.

Stuiver M, Reimer PJ. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35(1):215–230.

van der Plicht J, Ramsey CB, Heaton TJ, Scott EM, Talamo S. 2020. Recent developments in calibration for archaeological and environmental samples. Radiocarbon 62(4):1095–1117.

Warburton DA, editor. 2009. Time's up! Dating the Minoan eruption of Santorini: acts of the Minoan Eruption Chronology Workshop, Sandbjerg, November 2007. Aarhus Universitetsforlag.

Warren P. 1984. Archaeology: absolute dating of the Bronze Age eruption of Thera (Santorini). Nature 308(5959):492–493.

https://doi.org/10.1017/RDC.2023.35 Published online by Cambridge University Press