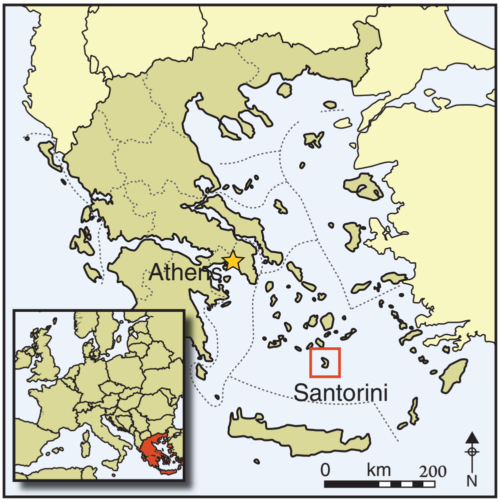
Bronze Age catastrophe and modern controversy: dating the Santorini eruption



The date of the volcanic eruption of Santorini that caused extensive damage to Minoan Crete has been controversial since the 1980s. Some have placed the event in the late seventeenth century BC. Others have made the case for a younger date of around 1500 BC. A recent contribution to that controversy has been the dating of an olive tree branch preserved within the volcanic ash fall on Santorini. In this debate feature Paolo Cherubini and colleagues argue that the olive tree dating (which supports the older chronology) is unreliable on a number of grounds. There follows a response from the authors of that dating, and comments from other specialists, with a closing reply from Cherubini and his team.

Keywords: Santorini, Thera, Minoan eruption, radiocarbon dating, tree-rings

Debate

The olive-branch dating of the Santorini eruption

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Introduction

The massive eruption of the volcano beneath the island of Thera (Santorini) in the middle of the Aegean Sea provides a fundamental datum point in the history of the Late Bronze Age civilisations of the eastern Mediterranean (Figure 1). The archaeological remains excavated at Akrotiri include impressive architecture, remarkable wall-paintings and large numbers of other finds and provide an unparalleled view of Aegean civilisation in the middle of the second millennium BC (Doumas 2010). The eruption occurred close to the height of the power and influence of the civilisation centred on Minoan Crete. Chronology is of major

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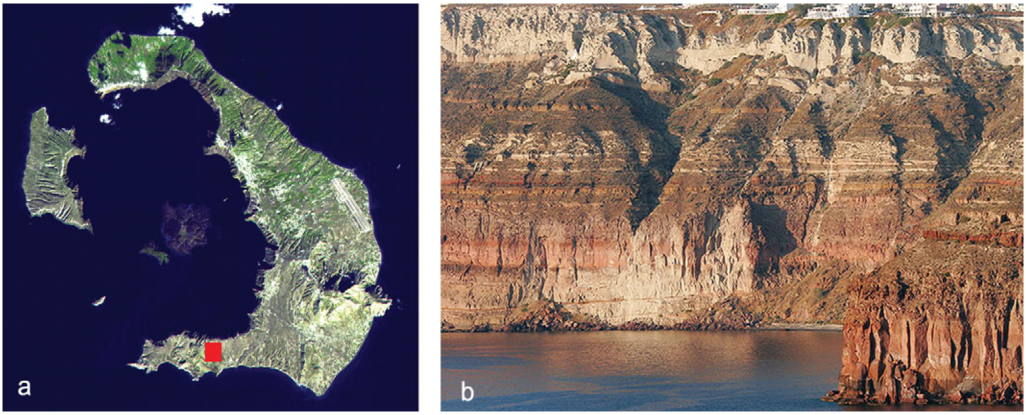

Figure 1. a) Satellite view of Santorini, showing the shape of the volcanic caldera (©NASA; Akrotiri is marked with a square); b) an example of the volcanic layers found across Santorini (© Tom Pfeiffer/www.volcanodiscovery.com).

importance for understanding the interconnections and influences between the ancient civilisations of the Aegean, Egypt and the Near East. The eruption has been dated near to the beginning of the New Kingdom in Egypt by a range of archaeological evidence. This dating appears to be strongly supported by the presence and sequence of Egyptian artefacts found in the Aegean as well as by large amounts of Cypriot pottery of various phases found both in Egypt and in one notable case also in the Theran volcanic destruction layer. It is also supported by the presence of pumice sourced to the Theran eruption in archaeological contexts in Egypt, the Near East and Cyprus (Doumas 2010), whereas all pumice found in earlier contexts has been sourced to other, earlier eruptions in the Dodecanese (Manning *et al.* 2006, 2009; Friedrich & Heinemeier 2009; Friedrich *et al.* 2009; Heinemeier *et al.* 2009).

Over the past 40 years, various studies have cited proxy evidence (ice-core acidity peaks and tree-rings) to place the Thera eruption around a century earlier, in 1628 or 1650 BC (LaMarche & Hirschboeck 1984; Baillie & Munro 1988). These apparent proxy connections (Pearson *et al.* 2009) are difficult to substantiate. They have recently gained apparent support (e.g. Manning *et al.* 2006, 2009; Friedrich & Heinemeier 2009; Friedrich *et al.* 2009; Heinemeier *et al.* 2009) from the publication of radiocarbon dates based on

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Figure 2. Cross-section of olive wood. Note the indistinct annual rings, caused by a lack of seasonality due to mild Mediterranean winters. Image: Turi Humbel.

the putative tree-ring sequence of a single olive branch buried in the tephra on Thera (Friedrich *et al.* 2006). This evidence has itself been the subject of extensive dispute (Warren 2006, 2009; Wiener 2009a & b). These discussions focused on the oscillating nature of the radiocarbon calibration curve over the relevant period, which makes it impossible to distinguish on radiocarbon grounds alone between an event around 1610 BC and one around 1525 BC. Radiocarbon measurements from tree samples of this period securely dated by dendrochronology, e.g. German oak, give similar radiocarbon ages for the decades centred on 1605, 1585, 1575, 1555, 1535 and 1505 BC, as do Anatolian junipers from Gordion for 1620, 1570, and 1540 BC (Wiener 2010).

Advocates of the earlier date have claimed that a series of measurements from the island of Thera in particular provide ^{14}C ages somewhat higher than *c.* 1610 BC. These measurements have, however, been the subject of considerable controversy with respect to their claimed accuracy of ± 8 years. The volcanic nature of the island of Thera also adds uncertainty regarding the possible effects of carbon reservoir depletion on ^{14}C values in the atmospheric air used for photosynthesis. In areas of the world where the necessary analysis of the volcanic atmosphere has been undertaken, such as Italy, radiocarbon from tree-rings gives dates that are a century or more early (Carapezza *et al*. 2009; Wiener 2010). Against this background, the radiocarbon measurements from the olive tree branch found buried in the eruption layer on Thera have added a new dimension to the discussion and have been considered critical evidence in the view of many (Warren 2009, 2010; Wiener 2009a & b, 2010).

Friedrich *et al.* (2006) reported the finding of a charred olive tree branch that they assume to have been alive when buried in tephra during the Minoan-period eruption. The authors of that study, aware of the fact that olive trees form irregular, barely identifiable tree-rings (Figure 2), used a 3D high-resolution X-ray Computer Tomography (CT) to define a putative 72-year tree-ring sequence on the cross-section of the olive branch that was to be radiocarbon dated. Wiggle-matching of four radiocarbon measurements from this branch against the calibration curve derived from other trees of known date (IntCal04) led them to assert that the calibrated age range of the outermost tree-ring of that olive branch was 1627–1600 BC (Friedrich *et al.* 2006).

The claim to have successfully wiggle-matched the ^{14}C sequence to the tree-ring chronology is critical to this proposal, inasmuch as the radiocarbon measurement from Santorini by itself is subject to the well-established 'reservoir effects' of ^{14}C-deficient carbon that characterise many volcanic islands and surrounding seas (Saurer *et al.* 2003; Carapezza *et al.* 2009; Frezzotti *et al.* 2009). It is highly probable that there were significant emissions of much more ancient pre-eruption volcanic CO_2 that were ^{14}C-depleted and fixed by the tree's photosynthesis and incorporated into its tree-rings (Saurer *et al.* 2003; Donders *et al.* 2013).

The assertion of a reliable ^{14}C 'wiggle-match' dating for Santorini is crucially dependent on the ability precisely to identify annual tree-rings in olive trees. In order to date the eruption, the tree-rings of the olive branch should reliably represent actual individual years, i.e. be annual tree-rings. That is not always the case in olive trees (Arnan *et al.* 2012). The last ring must also be contemporary with the volcanic eruption, i.e. from a live branch and not a dry, dead one that would reflect an earlier period. This in itself is a problematic issue in mature olive trees.

The results of a blind test involving several tree-ring laboratories to date tree-rings from olive trees currently growing on Santorini (Cherubini *et al.* 2013) clearly showed that measurements of tree-rings in olive wood from Santorini are highly unreliable owing to: a) intra-annual wood density fluctuations (e.g. Cherubini *et al.* 2003; Battipaglia *et al.* 2010; De Micco *et al.* 2012; Rossi *et al.* 2013); b) variability in tree-ring boundary structure (De Micco *et al.* in press); and c) restriction of cambial activity to shifting sectors of the circumference (Rossi *et al.* 2013), causing the tree-ring sequences along radii of the same cross sections to differ. We conclude that the dating of the Thera eruption based on the putative tree-ring sequence from a single olive tree must be considered with great caution.

Discussion

Ten tree-ring experts took part in the study to determine the number of tree-rings in olive trees currently growing on Santorini. The average number of tree-rings counted by the ten experts showed maximal deviations between 24.5 per cent to 56.3 per cent from the median, showing high variability among different experts' results (Cherubini *et al.* 2013). Even high-quality Neutron imaging of the tree-rings or SXFM mapping of elemental intensity for Ca failed to identify alternate elemental patterns within the xylem which might have been used to distinguish true annual tree-rings from inter-annual density fluctuations. Therefore, identification of olive wood tree-rings from Santorini by any means was found to be practically impossible.

A difference of 44 per cent—the average deviation in the olive tree-ring measurements by the ten experts—in the 72 putative tree-rings described by Friedrich *et al.* (2006) would result in a range of 40 to 104 years, rather than 72 as proposed. In contrast, Friedrich *et al.* (2006) estimate a maximal possible error of ±3 years for each of the four segments of the olive branch examined, giving a total of ±12 years. The results of Cherubini *et al.* (2013) pose a severe challenge to Friedrich *et al.*'s method and their dating of the Santorini eruption from a single olive branch tree-ring sequence and radiocarbon wiggle-match analysis. Without a safe identification of annual tree-ring boundaries there can be no certainty about the ^{14}C

dating. An erroneous wiggle-match leads inevitably to incorrect results. In this respect, even the very modest ±3 years claimed by Friedrich *et al.* is sufficient to cast doubt on their wiggle-match analysis.

Friedrich *et al.* knew about the difficulties of dating olive wood and tried to overcome them by using 3D high-resolution X-ray Computer Tomography (CT). They also presented a model in which they took these difficulties into account: they "...allow for a counting uncertainty of ±25% of the tree-ring count" (Friedrich *et al.* 2006: 548). In the light of Cherubini *et al.*'s (2013) results, it is questionable whether the level of uncertainty proposed by Friedrich *et al.* is sufficient. Furthermore, their final official date of 1627 to 1600 BC unfortunately did not consider the uncertainties admitted in their own supporting material.

Further doubt has been cast on this dating because of its incompatibility with radiocarbon determinations from sites not subject to obvious reservoir and volcano effects. There are also the numerous interconnections between pottery and other archaeological finds identical to those found in the volcanic destruction stratum at Santorini and materials found at other sites dated to *c.* 1525–1490 BC (Warren 2010; Wiener 2010). Interconnections with the well-established Egyptian historical chronology are now confirmed by 211 radiocarbon measurements (Bietak & Höflmayer 2007; Bronk Ramsey *et al.* 2010; Warren 2010; Wiener 2010). Finally, pumice chemically traced to the Minoan-period eruption of Santorini has been found at 15 sites in Egypt, the Near East, on Cyprus, the Anatolian coast and in the Aegean in contexts a century later than the dates proposed by Friedrich *et al.* Pumice from earlier contexts has in all cases been traced to earlier volcanic eruptions in the Dodecanese, and in one case to the Lipari volcano (Wiener 2010).

Friedrich *et al.* (2006) claimed that they have left a 50 per cent margin for error in counting the number of tree-rings, but if olive trees do not produce identifiable annual tree-rings, and no two laboratories can agree on the number of tree-rings observed (Cherubini *et al.* 2013), no secure dating is possible. In addition, there is no reason to assume that their sampled branch was necessarily alive when it was buried during the volcanic eruption. Olive trees in the Mediterranean frequently carry dead branches, sometimes very old ones.

Conclusions

The date of the Thera Minoan volcanic eruption is of major importance for understanding the relationships between the Late Bronze Age civilisations of Egypt, the Near East and the Aegean world. The contention that a charred olive tree branch was alive when buried in tephra during the Santorini eruption and had recognisable tree-rings allowed Friedrich *et al.* (2006) to date that eruption to 1627–1600 BC. If correct, this would have implied major changes in our understanding of developments in the Late Bronze Age civilisations of the Aegean and the eastern Mediterranean. Careful evaluation of their results is therefore of critical importance. Olive wood tree-rings are, however, very problematic in nature. A dendrochronological analysis of olive trees currently growing on Santorini (Cherubini *et al.* 2013) showed that it is impossible to determine the number of tree-rings. Accordingly, caution should be applied to the dating offered by Friedrich *et al.* and their proposal cannot be used to discount the date range of 1525–1490 BC proposed for the eruption from numerous other radiocarbon studies.

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