[Supplementary material]

Absolute tree-ring dates for the Late Bronze Age eruptions of Aniakchak and Thera in light of a proposed revision of ice-core chronologies

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A brief history of the Greenland ice core error

In the main text, we propose that chronological offsets within Greenland ice core chronologies have obscured the true volcanic history of the past four millennia and in particular confused efforts to obtain an absolute date for the Bronze Age eruption of Thera, Santorini in the seventeenth century BC. In this section we outline how, due to a combination of mis-placed confidence in the accuracy of the ice core dates, and an unfortunate coincidence, the chronological offset went unnoticed for decades.

Assuming that Thera was a large and chronologically isolated eruption, Hammer *et al*. (1980) originally interpreted a large acid signal in the Camp Century ice core at 1390±50 BC as probably caused by the sulphur output from Thera. Subsequently LaMarche and Hirschboek (1984) postulated that bristlecone pine frost rings—cellular damage caused by sustained freezing temperatures—are potential markers for large explosive volcanic eruptions. They identified a frost ring dating to 1627 BC, and speculated that it may have been caused by the climatic effects of the eruption of Thera.

As evidence mounted for a seventeenth century date for Thera, Hammer *et al*. (1987) assigned a large acidity spike at 1645±20 BC in the new Dye3 ice core to Thera. This date was later revised to 1641±5 BC in the GICC05 Timescale (Vinther *et al*. 2006). However, while the Dye3 date range bracketed the LaMarche and Hirschboeck date, Hammer *et al*. (1987), and subsequently Clausen *et al*. (1997) and Vinther *et al*. (2006), refused to consider that their acidity might be associated with the frost ring date 1627 BC. This refusal was based on their mis-placed confidence in the dating accuracy of their ice cores.

There are two reasons for this apparent confidence in ice core dating that require comment. First, Hammer and Clausen (*pers. comm*. 1989) believed that errors in ice layer counting were largely self cancelling (as likely to miss a layer, as to duplicate a layer count) and that

±20 was an overestimate, thus they suggested an actual error figure of ±7 years. However, Hammer and Clausen (1990: 177) also wrote:

> *If two well-measured deep cores exist, i.e. the Dye 3 and the new deep core (GRIP), it will be possible to improve the dating precision, because dating problems in one of the cores can to a large extent be solved by comparing the two cores year by year… we estimate that with two cores available, an error limit of ±5 years may be obtained for the 1645 BC event.*

So, before the GRIP and NGRIP ice records were available, Hammer and Clausen were predicting that the *error limit* on the dating estimate of the 'Thera' acidity would most likely be ±5 years. Turning to Vinther *et al*. (2006: Table 5), we find that the *maximum counting error* on the 'Thera' date in the new GICC05 ice chronology is given as 3640±5 b2k (b2k = number of years before AD 2000), as predicted; this dubious accuracy was only part of the ice chronology problem. The second issue centered on the date of an acid layer attributed to the historical eruption of Vesuvius (AD 79). We now know that the ice workers fell foul of Murphy's Law ("if something can go wrong, it will"). Here is how a fundamental error came about.

The Crête, Greenland, ice core indicated an acid layer at AD 934, and it was believed (wrongly) that this related to the historical eruption of Eldgjá, Iceland (Hammer *et al*. 1980). As the European Dye3, GRIP and NGRIP cores became available, each observed the Eldgjá acidity at what became AD 933±1. However, the American GISP2 core (drilled 30km from GRIP to allow replication), correctly dated the same Eldgjá acidity to AD 939±4 (Zielinski *et al*. 2004; Sigl *et al*. 2015). This discrepancy should have raised doubts but was ignored due to the triple replication provided by the three "independent" European cores (Dye3, GRIP and NGRIP), which were later used to construct the GICC05 timescale (Vinther *et al*. 2006). In reality the European ice core chronology GICC05 was around seven years too old before AD 1000 (Baillie and McAneney 2015). Enter Murphy's Law, in the form of a large acidity at around AD 88±1 (Sigl *et al*. 2015). In the European ice chronology each core dated this acidity spike to AD 79/80; clearly *attributable to Vesuvius* (see for example Barbante *et al*. (2013)). So confident were the ice core workers in their identification of Vesuvius within the ice cores that they reported this misidentified acid layer as a zero error date i.e. a date with zero uncertainty (Vinther *et al*. 2006: Table 4). We now also know that another acid spike around AD 1108±1 (Sigl *et al*. 2015) was originally identified as the AD 1104 eruption of Hekla 1 and also given status of a zero error date (Vinther *et al*. 2006: Table 4). This misplaced confidence in the accuracy of the ice chronology had consequences with respect to frost ring links to ice acidities.

As stated above, LaMarche and Hirschboeck (1984) had suggested that frost rings in bristlecone pines might be good indicators of explosive volcanic eruptions. This was rejected by the ice core community because, due to the ice dating error, there were few other direct linkages between the ice-derived volcanic acid dates and the precisely dated frost rings, before the second millennium AD. However, Baillie (2008, 2010) and Baillie and McAneney (2015) pointed out that if the ice dates were moved forward in time by seven years (prior to AD 1000) then a quite reasonable list of ice acidities coincided with frost ring dates during the first millennium AD (Salzer and Hughes, 2007), e.g.

Ice acid dates revised forward seven years	Frost ring dates
522, 536, 540, 574, 626, 682 etc	522, 536, 541, 574, 627, 681 etc

Shortly after the publication of Baillie and McAneney (2015), Sigl *et al*. (2015) confirmed that the GICC05 ice chronology needed to move seven years forward based on enrichment of cosmogenic isotopes in both ice *and* tree rings in AD 775. At this point it became clear that LaMarche and Hirschboeck (1984) had been correct and bristlecone frost rings are good indicators of explosive volcanic events. Just how unlucky the ice workers had been is shown by the occurrence of only four major acidities between AD 500 and 50 BC (Clausen *et al*. 1997). Four major acid signals in 450 years and one falls around seven years *after* Vesuvius.

Radiocarbon evidence for a seventeenth century BC eruption of Thera

We present in Figure 2 of the main paper a summary of radiocarbon analyses of material directly associated with the eruption of Thera. These materials consist of short lived samples from the Akrotiri Volcanic Destruction Layer (VDL) and an olive branch, presumably killed and buried by the eruption, recovered *in situ* from pumice deposits on Santorini. In Figures S1-S5 below we provide the radiocarbon calibrations for the data provided in Figure 2 of the main text. Calibration is performed using IntCal13 (Reimer *et al*. 2013), and modeled using OxCal 4.3.1 (Bronk Ramsey 2009).

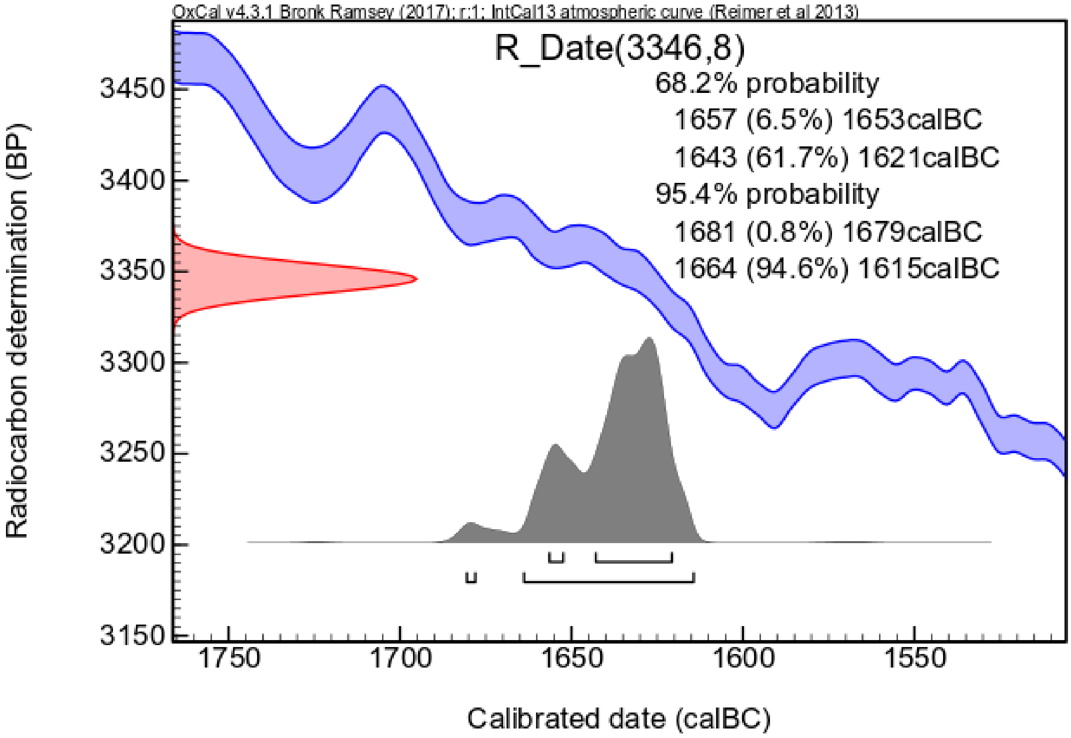

Figure S1. The weighted mean of short lived samples recovered from the Akrotiri VDL. This radiocarbon calibration employs a sub-set of 25 dates from 28 samples reported in Manning *et al*. (2006). Three of the samples are excluded on the grounds that this 3-date subset has too large a spread in values, and their exclusion or inclusion does not affect the practical analysis, having little effect on the weighted mean due to the down-weighting from large measurement errors (see Manning (2014) for more details).

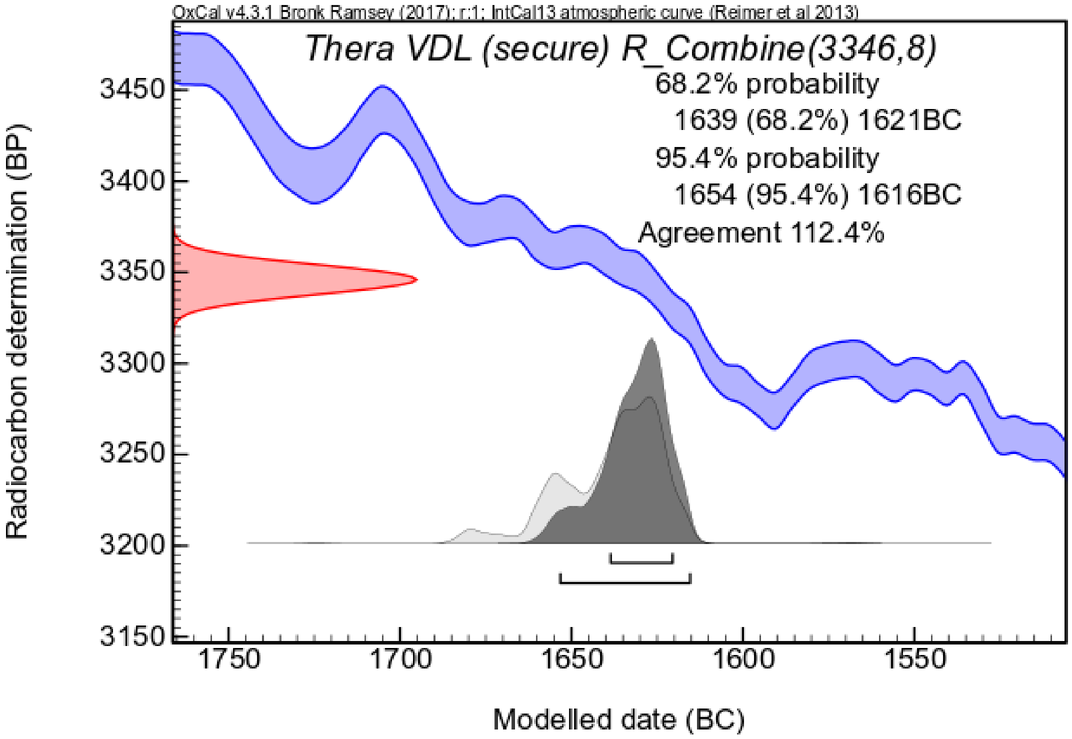

Figure S2. Using the same 25-date subset of short lived samples the calibrated date is obtained by employing a model in which the Akrotiri VDL is included as a Phase within in a Bayesian sequence analysis for the successive LMIA → LMIB → LMII archaeological phases (see Manning *et al*. (2006) and Manning (2014)). The light grey area gives the weighted mean of the 25-date subset on its own, while the darker grey area gives the calculated, or modelled, age range from the Bayesian model.

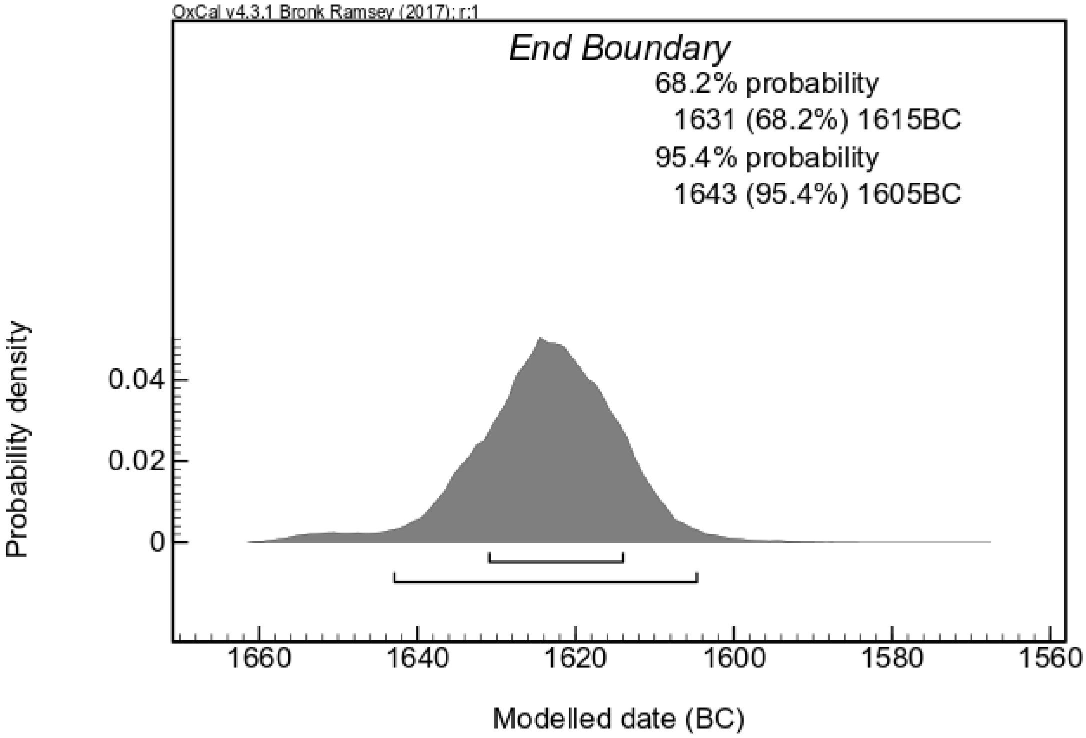

Figure S3. The date for the end of the Akrotiri VDL using the 25-date subset but grouped as a single Phase with a Tau_boundary at the start of the Phase and a Boundary at the end of the Phase (after Hölfmayer (2012)). Such a model assumes an exponential distribution of dates with most dates near the end of the Phase.

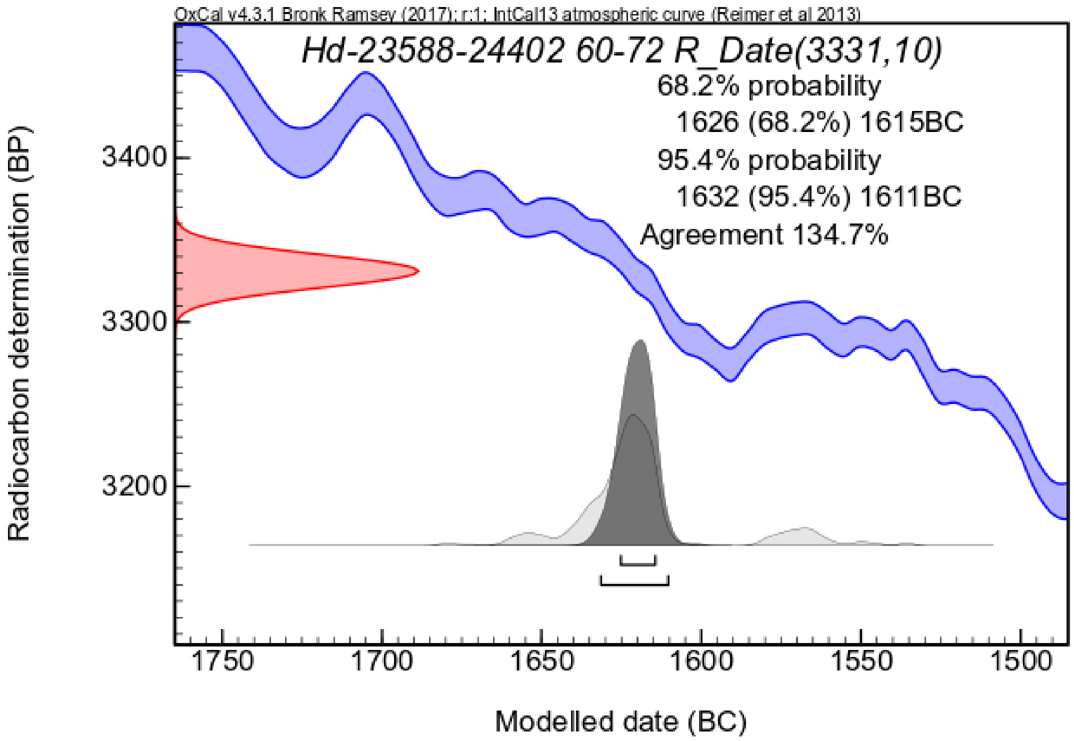

Figure S4. A wiggle-match calibrated date range for the outer section (rings 60-72) of the olive branch recovered from the pumice on Santorini after assuming near exact knowledge of the true ring count (after Friedrich *et al*. (2006)). The calibrated date range is for the middle ring of the outer section, and so the date of the last growth ring can be determined by adding six years to the range.

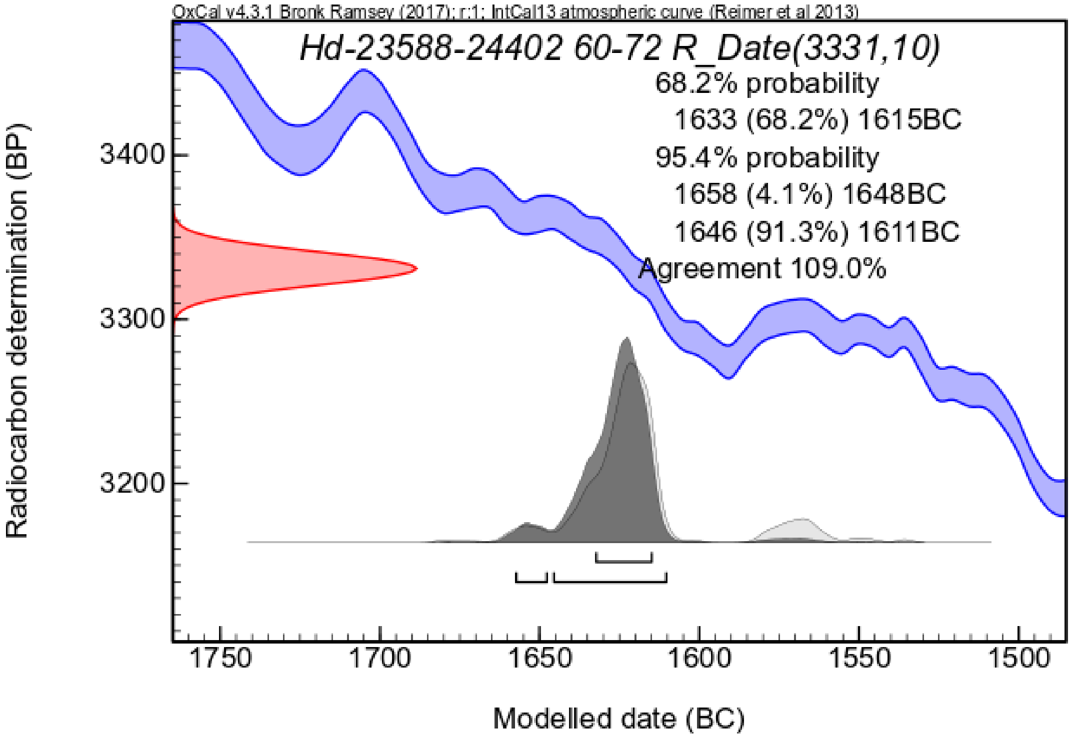

Figure S5. The calibrated date range for the outer section (rings 60-72) of the olive branch recovered from the pumice on Santorini assuming no knowledge of the number of tree rings. As such, the calibration is performed using a Sequence analysis from inner most to outer most segments in an ordered sequence (a pseudo-wiggle match). The calibration gives a *terminus post quem* date for the eruption of Thera since we are assuming no tree-ring counting information. Manning *et al*. (2014) have argued that the outer most ring can be no more than 10-years after the midpoint of the outer section of the outer sequence and so suggest that the date for the eruption to be *after* 1636 CalBC (i.e. most likely 1636–1600 cal BC in the 91.3 per cent range of the 95.4 per cent probability range).

Does the Venus Tablet of Ammisaduqa record the eruption of Thera?

It has been suggested that an indirect record of a dust veil event is recorded in a Babylonian astrological tablet; Tablet 63 of Enuma Anu Enlil (de Jong and Foertmeyer 2010). This tablet, known as the Venus Tablet of Ammisaduqa, records the observed helical risings and settings of the planet Venus over a 21-year period, beginning in the first year of the reign of King Ammisaduqa. Due to the relative motions of Earth and Venus around the Sun, Venus disappears from our skies for less than a few weeks during inferior conjunction (Venus between Earth and the Sun), and for around two months during superior conjunction (Venus behind the Sun). However, the Venus tablet records that during the twelfth year of observations, Venus is apparently invisible for around five months during superior conjunction, three months longer than expected.

The "best-fit" dates for year one of the Venus observations are 1702, 1646, 1638 and 1582 BC (Huber *et al*. 1982) and so it has been proposed that the anomalous invisibility of Venus could be due to a volcanic dust veil event caused, specifically, by the eruption of Thera, if the records begin in 1638 BC, in line with radiocarbon dates for the eruption (de Jong and Foertmeyer 2010). In this scenario, the twelfth year record would correspond to the year 1627 BC, a date which has been associated with Thera since 1984 (LaMarche and Hirschboek 1984).

By re-dating the ice cores, we show that ice containing a large volcanic acid signal, as well as Aniakchak-like tephra—but *not* Thera-like tephra (Coulter *et al*. 2012)—is now dated to around 1627 BC, proximate to one possible time frame of the five month invisibility of Venus. The question then is, if the Venus Tablet does indeed record a dust veil event, and if the first year of the Venus Tablet is 1638 BC, which eruption—Aniakchak or Thera—originated the dust veil event?

A prolonged dust veil event occurs when a large eruption column penetrates the tropospheric ceiling, contaminating the overlying stratosphere with volcanic aerosols. The dust veil event of AD 536 recorded across Europe and the Mediterranean (Stothers 1984), may have been caused by one or more high latitude northern hemisphere eruptions; chemical analysis of three types of tephra recovered from AD 536 ice found the tephra shards to be similar to volcanic systems in the Aleutian arc (Alaska), Northern Cordilleran volcanic province (British Columbia), and Mono-Inyo Craters area (California) (Sigl *et al*. 2015). This dust veil event may have prevented the Chinese from observing the star Canopus (the second brightest star in the night sky) at either equinox in that year (see Arjava (2005) and references within). Thus, if the Venus Tablet does record a dust veil event observed in the locality of Babylon, it does not necessarily imply an origin from a reasonably nearby volcanic eruption, such as Thera.

If we assume that the first year of the Venus Tablet is indeed 1638 BC, then the anomalous disappearance of Venus during superior conjunction occurs between 9 May and 19 October 1627 BC (de Jong and Foertmeyer 2010) in the Julian calendar (or 25 April and 5 October in the Gregorian calendar). Thus Venus becomes invisible 41 days earlier than astronomically calculated, and becomes visible again 48 days later than calculated (de Jong and Foertmeyer 2010). Note that 9 May 1627 BC does not necessarily imply the date for the eruption that caused the proposed dust veil event, since the volcanic dust veil may have begun months before. Indeed, investigating the atmospheric extinction around this time, de Jong and Foertmeyer (2010) place the date of eruption between 13 October 1628 and 9 May 1627. For simplicity of argument we shall assume 9 May to be the start of the dust veil event for the following discussion, while remembering that it may have begun earlier.

We have no information on the seasonality of the eruption of Aniakchak, but we do have information regarding the seasonality of Thera. Sewell (2001) and Manning and Sewell (2002) modelled the dispersion of tephra due to seasonal winds and found that Thera most likely erupted in either spring or summer. A more recent and more sophisticated model by Johnston *et al*. (2012) draws similar conclusions, with perhaps a better match to the observed dispersal pattern for a summer (May-July) eruption.

Panagiotakopulu *et al*. (2013) estimated that Thera erupted in early or early-mid summer, perhaps June or early July, based upon activity of the bean weevil, *Bruchus rufipes,* preserved in crop storage jars from the West House of Akrotiri. One could question whether the crops were stored in the same year as the eruption of Thera, or whether the crops were stored perhaps one or two years before the eruption. Panagiotakopulu *et al*. (2013: 686-87) have concluded from the insect evidence that:

> *"The insects recovered, although charred were well preserved... [were] spread throughout the seed assemblage, indicating a population which was active at the time of the charring event. The overall picture from the insects found in pithos 1 was that death was a result of a single event as opposed to a gradual process, and that it had probably taken place soon after the crop was placed in store. Had the [insects] been part of long-term storage in the pithos, microbial and fungal attack on the dead pests, leading to some poor preservation, would have been evident."*

Unfortunately the terms "soon after" and "long-term" are not quantitative but Panagiotakopulu *et al*. report that that specimens preserved in the jars include most stages of the bean weevil's life cycle (larvae, pupae, imagines yet to emerge and *still within the bean,* and adults). Since *B. Rufipes* complete their life cycle outdoors and not within storage—Bruchid females require a meal of pollen from flowers to reach sexual maturity—the strong suggestion is that the crop was probably stored in the same year as the Thera eruption.

It is also not clear whether Panagiotakopulu *et al*.'s suggested month of eruption is in the Julian or Gregorian calendar, but we presume the Gregorian calendar since June and July are currently the months of early and early-midsummer (in the Gregorian calendar the date of vernal equinox (and thus the seasons) is fixed, unlike the Julian calendar in which the date of the vernal equinox (and hence seasons) drifts over time at a rate of around eight days per millennium). However, regardless of which calendar Panagiotakopulu *et al*. employed, a date of June/early-July in either calendar system will always be later than 9 May in the Julian calendar system in the seventeenth century BC.

So if Thera did not erupt until June/July 1627 BC, then it could not have originated the Venus obscuring dust veil event that began in early May 1627 BC (or before). If Thera erupted in June/July 1628 BC, then it is unlikely to have caused the dust veil event which did not begin until at least *after* October 1628. This leaves us with the possibility that *if* year one of the Venus Tablet of Ammisadaqu is 1638 BC and *if* the anomalous invisibility of Venus in year 12 is a symptom of a volcanic dust veil, then it may be the effects of Aniakchak that are in fact recorded in the Venus Tablet. If correct, this does not rule out the possibility that Thera erupted shortly after Aniakchak, and possibly contributing to the dust veil event, but even if this is the case we cannot use the Venus Tablet as a unique proxy record for dating the eruption of Thera.

Finally, if we return to the list of ”best fit dates” for year one of the Venus Tablet, we note that another possibility for the commencement of Venus observations is 1646 BC, which would place the date of the anomalous invisibility of Venus at superior conjunction between 7 May and 18 October 1635 BC. This invisibility is broadly compatible with radiocarbon evidence (in particular the Akrotiri VDL and olive branch pseudo-wiggle match dates), but lacks supporting proxy evidence from ice core or tree-ring chronologies. It also suffers from similar arguments outlined above with regards the Venus Tablet dates for the anomalous invisibility of Venus apparently predating the Thera eruption as per the preserved insect evidence.

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