

The Minoan eruption of Santorini radiocarbon dated by an olive tree buried by the eruption

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Abstract

In 2006 we published a radiocarbon dating, 1613 BC, for the Minoan eruption on Santorini with an unparalleled precision of ± 13 calendar years.¹ It was based on the unique find in the caldera wall of Santorini of a branch of an olive tree that had been buried and preserved in an upright, life, position by the pumice of the eruption. 72 tree rings were identified by X-ray tomography, and the high precision was achieved by wiggle matching the ¹⁴C results of the time series of four contiguous sections of tree rings to the radiocarbon calibration curve. Since the trees were growing at an altitude of 150 m above sea level and at a distance of more than 2.5 km from the active volcanic zone on Santorini, it is unlikely that the radiocarbon values published in 2006 could have been affected by old CO₂. Because of the clear association of the tree and its outermost growth ring with the geological/archaeological event of the eruption, the date represents the best combination of directness and precision in any attempt so far of a science based chronology of the Minoan eruption.

While in broad agreement with other science dating attempts, there are some who claim that it is completely irreconcilable with the traditional archaeological dates of the late 16th century BC, or later, based on cultural linkage (pottery typology) and Egyptian Chronology. To resolve the conflict, we need to take a careful look at the implicit and explicit underlying assumptions in the two methods. As we do not possess the expertise to evaluate the results of the archaeological approach, this paper will deal with the details of the find of the olive branch and its radiocarbon dating by wiggle matching as well as a balanced assessment of the possible sources of error.

Introduction

Thirty years ago, all the radiocarbon age determinations of material from Akrotiri were single measurements of short-lived material such as seeds. For example, the radiocarbon laboratory in Copenhagen dated seeds of 'faba' beans (*Lathyrus clymenum*) and lentils (*Lens culinaris* Medik.) that were found in jars in the excavations at Akrotiri. However, when they were calibrated using the calibration curve of that time,² the original precision of the measurement was lost owing to a flat section in the radiocarbon calibration curve.³ The calibrated results were around 1645 BC, which at that time corresponded to the acid signal found in the DYE3 ice core in Greenland.⁴

Since then, things have changed. Today we use the IntCal04 calibration curve that has many improvements. However, people have objected that the curve has been smoothed. Radiocarbon measurements on recent trees performed in different laboratories contributed to the new calibration curve (Fig. 1). They give a fairly good agreement among the measured samples. IntCal04 shows that errors of individual calibration measurements range from ± 12 –15 years on samples averaging 10 tree rings. No difference can be detected between the regions whence the trees come, even at high-precision error levels. Furthermore, there is no evidence of anomalous atmospheric ¹⁴C levels in the Aegean.

Manning and his co-workers have dated samples which consist almost exclusively of short-lived or-

¹ Friedrich *et al.* 2006.

² Pearson & Stuiver, 1986.

³ Friedrich *et al.* 1990.

⁴ Hammer *et al.* 1987.

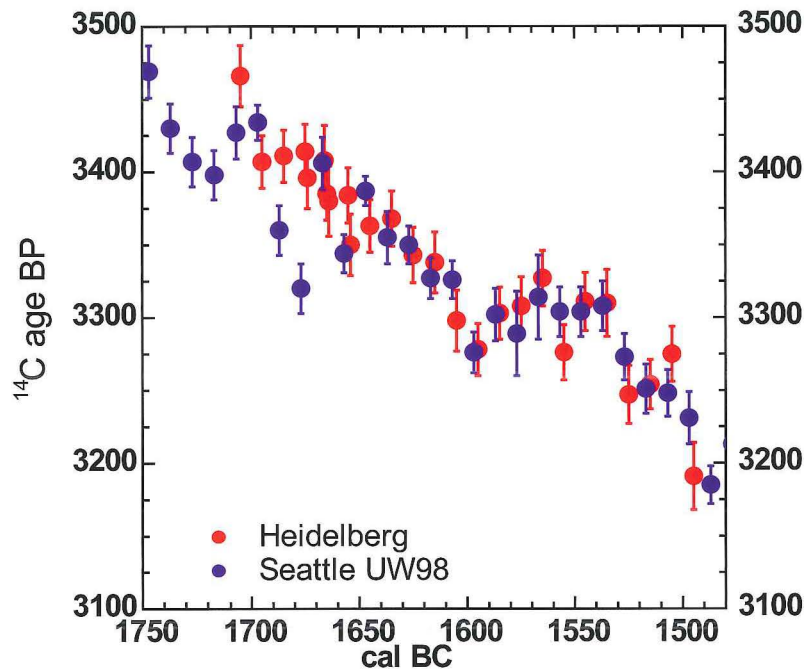


Fig. 1. Relevant part of the calibration curve, ranging from 1500-1750 BC. It is based on German oak measured at Heidelberg (red) and Seattle (blue).

ganic materials from the Akrotiri excavations and other localities in the Aegean.⁵ Their samples were measured in radiocarbon laboratories at Vienna, Oxford, and Heidelberg. When the samples were calibrated in combination with stratigraphic information, the Minoan eruption was placed in the range 1660-1613 BC with 95.4% probability. However, the most precise and direct date was derived from a branch which is part of the remains of an olive tree that was buried alive, in life position, in the pumice of the Minoan eruption on Santorini

as shown in Figs 2-4 and discussed in Friedrich & Heinemeier, this volume.

Radiocarbon measurements of the olive branch

Using 3D X-ray tomography it was possible to count 72 year rings (*cf.* Frontispiece facing title

⁵ Manning *et al.* 2006.

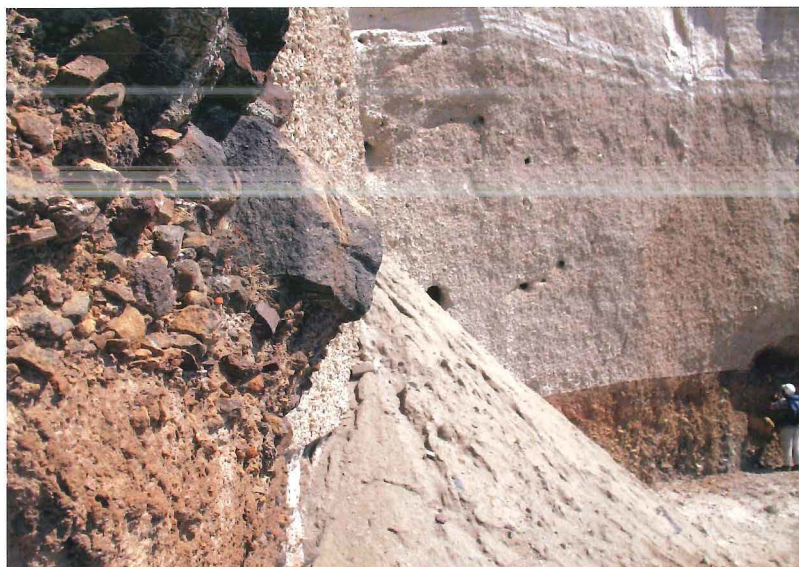


Fig. 2. The photo shows the locality in June 2007 where the remaining branches of the two trees were found. Part of a wall from the Bronze Age is visible in the upper left corner. In the centre, the mould where the first olive branch was excavated from its life position in the pumice of the Minoan eruption is seen, more than a metre above the pre-eruption soil surface (red layer). The hole is visible above the head of Tom Pfeiffer, where a branch of the second olive tree was dug out.



Fig. 3. The first look at the branch of the first tree, while still embedded in the pumice of the Minoan eruption.



Fig. 4. A polished section of the branch. Growth rings are barely traceable.

page). They were sampled in four groups, and the mean radiocarbon age of each group of rings could be fitted to the IntCal04 calibration curve. A few test samples were run at the AMS ^{14}C Dating Centre in Aarhus (Fig. 5), showing that the dates lay within the range of those proposed for the Minoan eruption. The final, high-precision radiocarbon measurements were performed at the conventional radiocarbon laboratory in Heidelberg (Fig. 6) that had earlier measured the relevant section of the calibration curve (Fig. 1). The radiocarbon ages of the four year-ring groups were wiggle matched to the calibration curve IntCal04. The high precision of the calibrated date of the Minoan eruption was obtained due to the fact that we knew the number of tree rings in each group and thus the time gap be-

tween the central ring in each group. The option, ‘defined sequence’ of the Oxcal 3.0 programme was used with these known gaps, resulting in the final calibrated age range 1627–1600 BC (1613 ± 13 BC) with a probability of 95%.⁶ Several tests were run in order to demonstrate the robustness of the measurements with regard to uncertainties in ring counting or growth irregularities of olive trees. Thus, even when we use the option, ‘variable sequence’ to take an uncertainty of 50% in the ring count into account, these limits are increased by only a decade (cf. Frontispiece, facing title page, bottom).⁷

⁶ Friedrich *et al.* 2006.

⁷ See Frontispiece and figs 7–8 and online material, table S2 in Friedrich *et al.* 2006.



Fig. 5. AMS accelerator at the Department of Physics, Aarhus University, Denmark, where the first samples were measured.

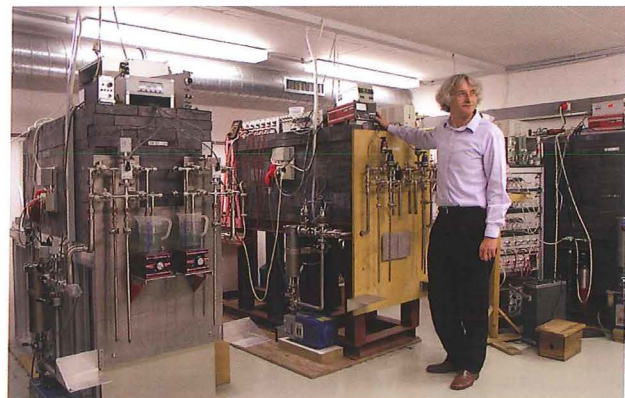


Fig. 6. Bernd Kromer and his Radiocarbon Laboratory in Heidelberg, where the final measurements were made.

To test the accuracy of the conventionally measured radiocarbon age of the last tree ring section, we have compared this to earlier measurements. Thus all of the other measurements for the eruption⁸ and the last tree ring of this sample agree (they pass a Ward and Wilson chi squared test: $df=27$ $T=32.6$ cf. 5% 39.9). The relevant input dataset is:

```
R_Combine()
{
R_Date( "OxA-11817", 3348, 31);
R_Date( "OxA-11818", 3367, 33);
R_Date( "OxA-11820", 3400, 31);
R_Date( "OxA-11869", 3336, 34);
R_Date( "OxA-12170", 3336, 28);
R_Date( "OxA-12171", 3372, 28);
R_Date( "OxA-12175", 3318, 28);
R_Date( "OxA-12172", 3321, 32);
R_Date( "OxA-1552", 3390, 65);
R_Date( "OxA-1555", 3245, 65);
R_Date( "OxA-1548", 3335, 60);
R_Date( "OxA-1549", 3460, 80);
R_Date( "OxA-1550", 3395, 65);
R_Date( "OxA-1553", 3340, 65);
R_Date( "OxA-1554", 3280, 65);
R_Date( "OxA-1556", 3415, 70);
R_Date( "Hd-5048/5519", 3490, 80);
R_Date( "Hd-6059/7967", 3140, 70);
R_Date( "K-5352", 3310, 65);
R_Date( "K-5353", 3430, 90);
R_Date( "K-3228", 3340, 55);
R_Date( "K-4255", 3380, 60);
R_Date( "VERA-2756", 3317, 28);
R_Date( "VERA-2757", 3315, 31);
R_Date( "VERA-2758", 3339, 28);
R_Date( "VERA-2757R", 3390, 32);
R_Date( "VERA-2758R", 3322, 33);
// Friedrich et al
R_Date( "Hd-23588/24402", 3331, 10 );
};
```

This suggests that all of the measurements for the time of the eruption (presumably in different areas of the island) give the same results within the measurement precision.

If there is a local environmental effect that “explains” the radiocarbon results for a *c.* 1520 BC erup-

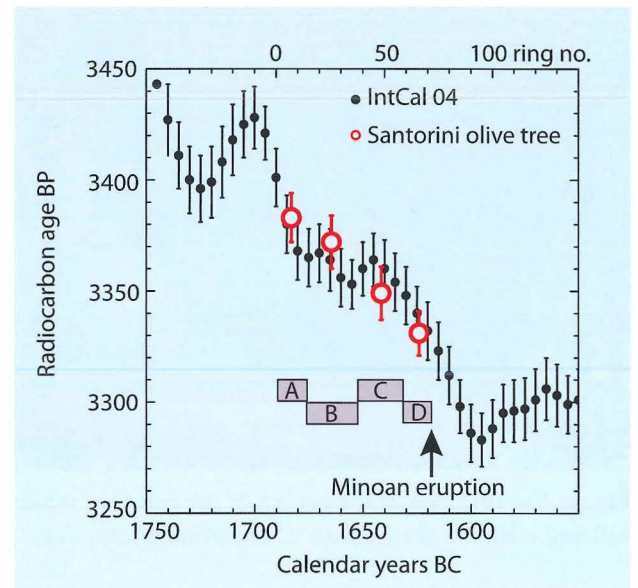


Fig. 7. Radiocarbon dating of four groups of growth rings (A-D). The groups contain 13 to 23 rings, here calibrated (“wiggles-matched”) to the latest calibration curve IntCal04.

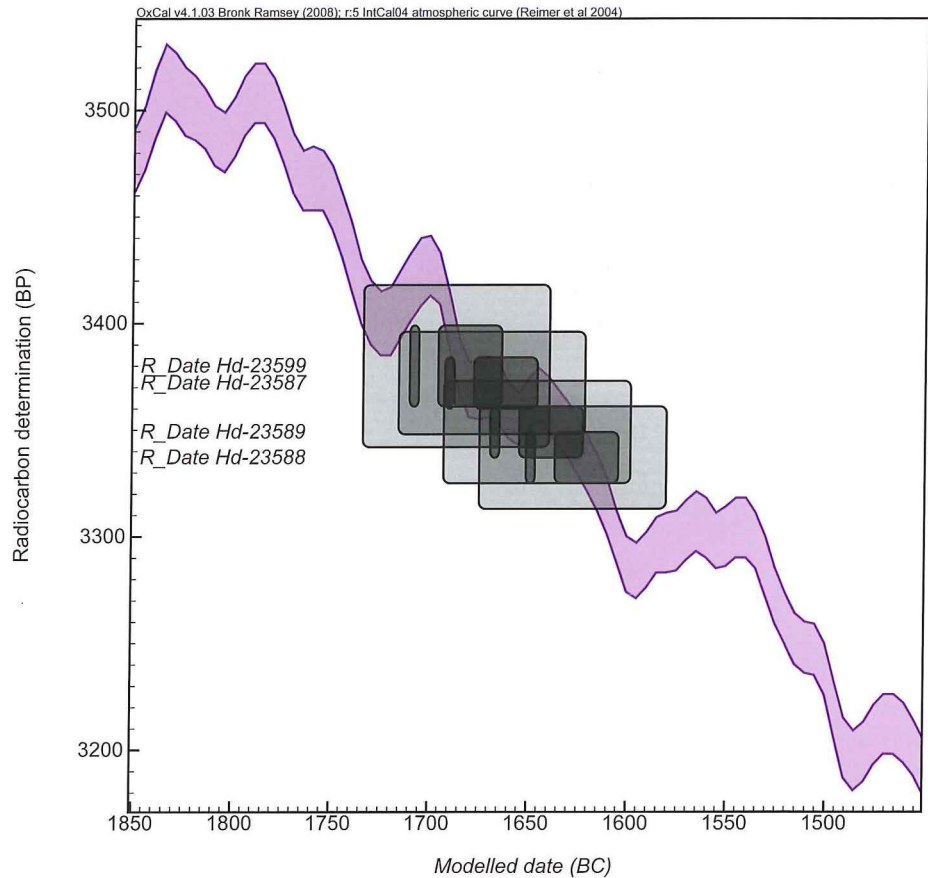
tion, it is clear that it cannot really be a local vent or something which varies rapidly in the time leading up to the eruption – this is partly shown by good agreement above and also by the fact that there are no obvious anomalies in the sequence from the olive sample (Fig. 7).

One could consider whether there might be a much more widespread local reservoir offset, fairly consistent over the life of the wood measured. However, given the consistency of the measurements with the calibration curve this would indeed have to be very constant, and there is no particular reason why there should be such an effect in this region, solely for this period.

We have considered the effect of allowing some variation in the local CO_2 reservoir by using a Delta-R correction with a mean of zero in the calibration. No appreciable effect is seen for an uncertainty of 20 years (see Fig. 8). Essentially, one has to make the uncertainty on any long term local reservoir average as large as 40 years before one sees any significant probability of an eruption date near 1500 BC, and then only because this allows (at

⁸ Short lived material from Manning *et al.* 2006a.

Fig. 8. Calibration curve with calibrated ages (95% probability) indicated in light grey, assuming an uncertainty of 20 years in a hypothetical local CO₂ reservoir offset around Santorini. No significant probability of an eruption date later than 1580 BC is seen.



close to 2 standard deviations) a consistent offset of 70–80 years.

Finally there is the question of the validity of the calibration curve in this period. Again, the results from Santorini presented here as well as sequences from Miletos and Gordion⁹ show that wood growing in this period mirrors what is shown in the IntCal curve for this period – so there is no really good evidence that the calibration curve itself is wrong. Further, in many ways, the dating of the olive branch is less sensitive to deviations in the calibration curve than the measurements on the short-lived material from Santorini since the latter could be influenced by a hypothetical very short unperceived anomaly in the curve – something which would not apply to the olive branch.

The leaves

In the fine dust of the exposed precursor layer of the Minoan eruption, a high concentration of olive

leaves was found under each tree, but none in the area between the trees (Friedrich and Heinemeier, this volume), indicating that both trees were alive when buried by the eruption. For the purpose of supplementary radiocarbon dating, we have made several attempts to collect some of these leaves, but while their structure seems perfectly preserved *in situ*, the material turns into dust when handled, and no organic material remains for dating. The same effect is seen in the roots found under both trees.

However, even if it had been possible to make a high-precision radiocarbon dating of the leaves, the results would not contribute to increase the precision of the determination of the eruption date, since they are single samples limited to a single year of life. It is widely assumed that material which can be dated to a single year (grain, leaves, pits or stones) is more reliable for giving an indication of the date of the deposit. However, in contrast to the

⁹ Manning *et al.* 2001; Galimberti *et al.* 2004; Bronk Ramsey *et al.* 2004a; Kromer *et al.* 2001.

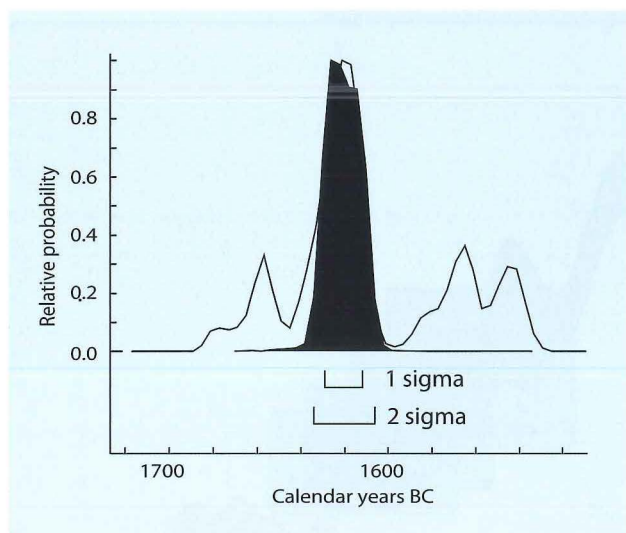


Fig. 9. The diagram shows the benefit of wiggle matching. The probability plot of the last group of growth rings has been calculated using the programme OxCal03. The black “column” is a result of calibrations of the last group of rings against the calibration curve IntCal04. As this column shows a narrow, approximately Gaussian distribution, the result is rather exact. Without wiggle matching (the thin line), however, the final result after calibration would be rather inexact.

sequences of tree-rings sampled from the branch, organic materials with a life span of a single year cannot offer the necessary data to arrive at a precisely calibrated date, since the calibration curve has wiggles and is thus not a straight line. Thus – were we to achieve what has hitherto proved impossible – we know in advance that any potential future leaf samples would show the same ambiguous calibrated dates, with peaks separated by troughs decades apart, exactly as do the many similarly short-lived samples previously dated from the Akrotiri excavation (see also the example of no wiggle matching in Fig. 9).

Discussions and questions

The radiocarbon age of the olive branch from Santorini has inspired lively discussions among scholars. Two main issues were debated: 1) was the tree alive when it was buried by the ashes of the Minoan Eruption? 2) Is it likely that old volcanic CO₂ might

have influenced the result of the radiocarbon dating? Concerning the first issue, we are sure that the tree was alive, as olive leaves were found on the ground at the growth place of the trees, embedded in a 4 cm thick layer of fine volcanic dust. The leaves are found within the layer – not under it, which means that a hot cloud of volcanic dust surrounded the olive trees and caused the leaves to desiccate and fall. We found the leaves only in the immediate vicinity under each tree indicating that the trees cannot have been dead.

Were the olive trees affected by old CO₂?

Since the olive trees grew on a volcanic island, it is also relevant to consider the question of whether the radiocarbon dates might have been influenced by old CO₂ from the magma chamber. By studying the geological situation of that time, the morphology and the distance of the localities from which the radiocarbon samples were taken in comparison to the emanation points of old CO₂, one can answer this question. Concerning the shape and morphology of the ring island in the Bronze Age we have detailed knowledge from fieldwork through the past three decades and the reconstructions presented by various geologists are quite similar.¹⁰ According to these reconstructions, the sites of the Akrotiri and the nearby Potamos excavations as well as the growth place of the olive trees lie at a safe distance from any potential influence of old CO₂ (Friedrich & Heinemeier this volume, 57 Fig. 3). Furthermore, the same sites show direct evidence of a long period of volcanic inactivity. At Akrotiri and Potamos, the Minoan pumice was deposited directly on top of the Cape-Riva ignimbrite – from the last major eruption prior to the Minoan – which has been dated at 21,000 calendar years BP.¹¹ (See also Fig. 10).

Studies in Germany (Laacher See) and on Santorini (Palea Kameni) have shown that plants grow-

¹⁰ Friedrich *et al.* 1988; Eriksen *et al.* 1990; Druitt *et al.* 1999; Heiken & McCoy 2000.

¹¹ Pichler & Friedrich 1976.

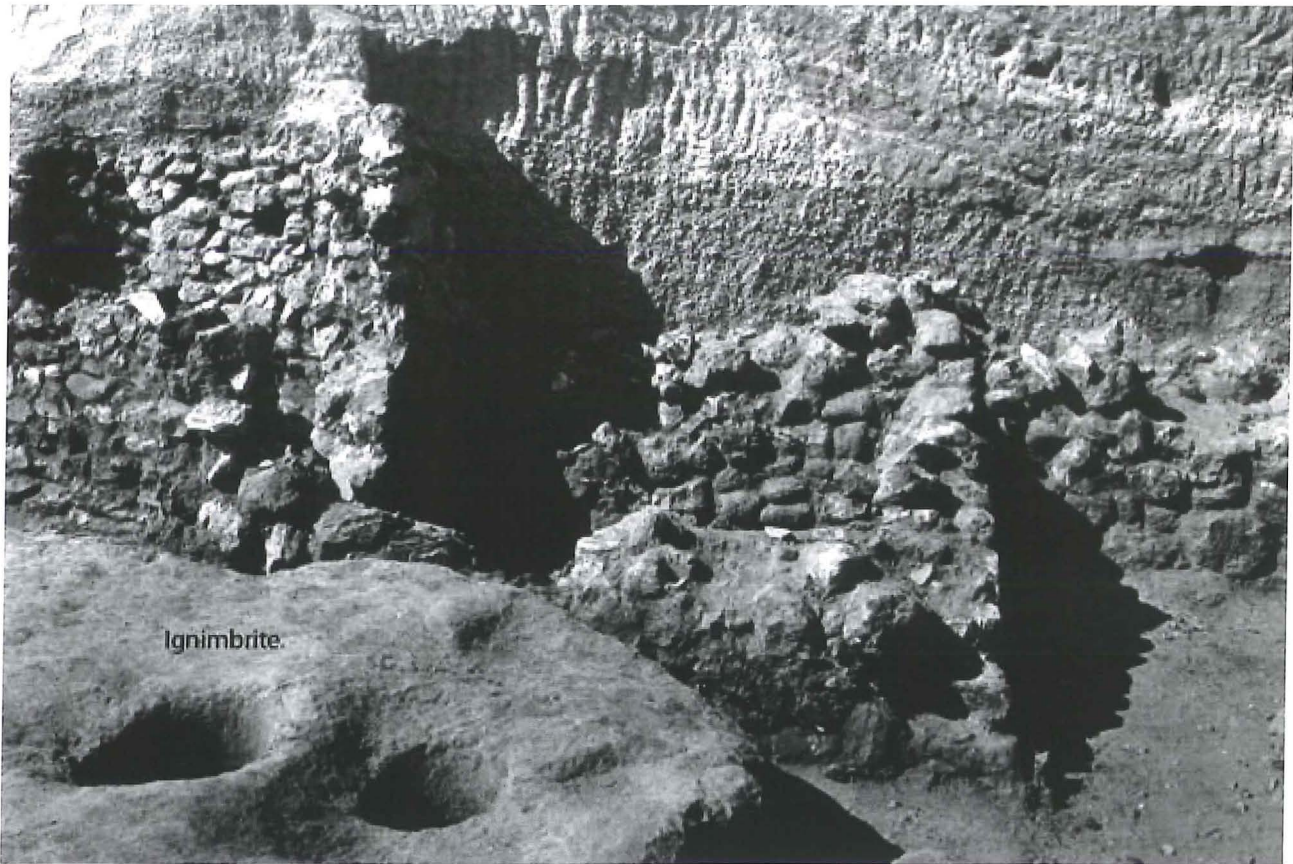


Fig. 10. The photo shows the excavation by Robert Zahn in the Potamos valley at Akrotiri around 1900. To the left, wall remains directly on the Cape Riva ignimbrite, and in the middle of the picture walls that were built below the ignimbrite. To the left the Cape Riva ignimbrite (with two manmade holes) has a radiocarbon age of about 21,000 calendar years BC. The fact that the eruption products of the Minoan eruption are deposited directly on the ignimbrite testifies the existence of a period of quiescence that lasted about 17,000 calendar years. The walls were partly eroded away by the winter rain. Now and then, rainwater formed a creek (Potamos) that left younger sediments, covering the walls. (Photo: German Archaeological Institute, Athens).

ing close to an emanation source of old CO_2 , falsely give old radiocarbon ages.¹² However, these studies also show that the effect is locally restricted, in agreement with theoretical calculations of atmospheric mixing. Since (a) the distance between the growth-site of the olive tree and the nearest point in the active volcanic zone is about 3.5 kilometres; (b) the site is about 5 kilometres away from the crater of the Minoan eruption; and (c) the tree was found on top of the pre-eruption caldera rim and thus in an area with excellent air circulation – ensuring both horizontal and vertical atmospheric mixing – it is unlikely that contamination with old CO_2 could have affected the olive tree. Last but not least, neither faults nor old fumarolic fields nor

sites with iron oxide deposits were observed in the neighbourhood of the tree. Thus the tree rings must be considered a reliable record of atmospheric CO_2 in its seven decades of life prior to the eruption.

The Minoan eruption was one of the most violent in human history. Its unusual strength was the result of a long period of inactivity prior to the eruption. During the past twenty thousand years, all volcanic activity on Santorini, including emanation of CO_2 , has been confined to a structurally weak tectonic zone running northeast-southwest from the volcanoes of the Christiana Islands in the

¹² Bruns *et al.* 1980.

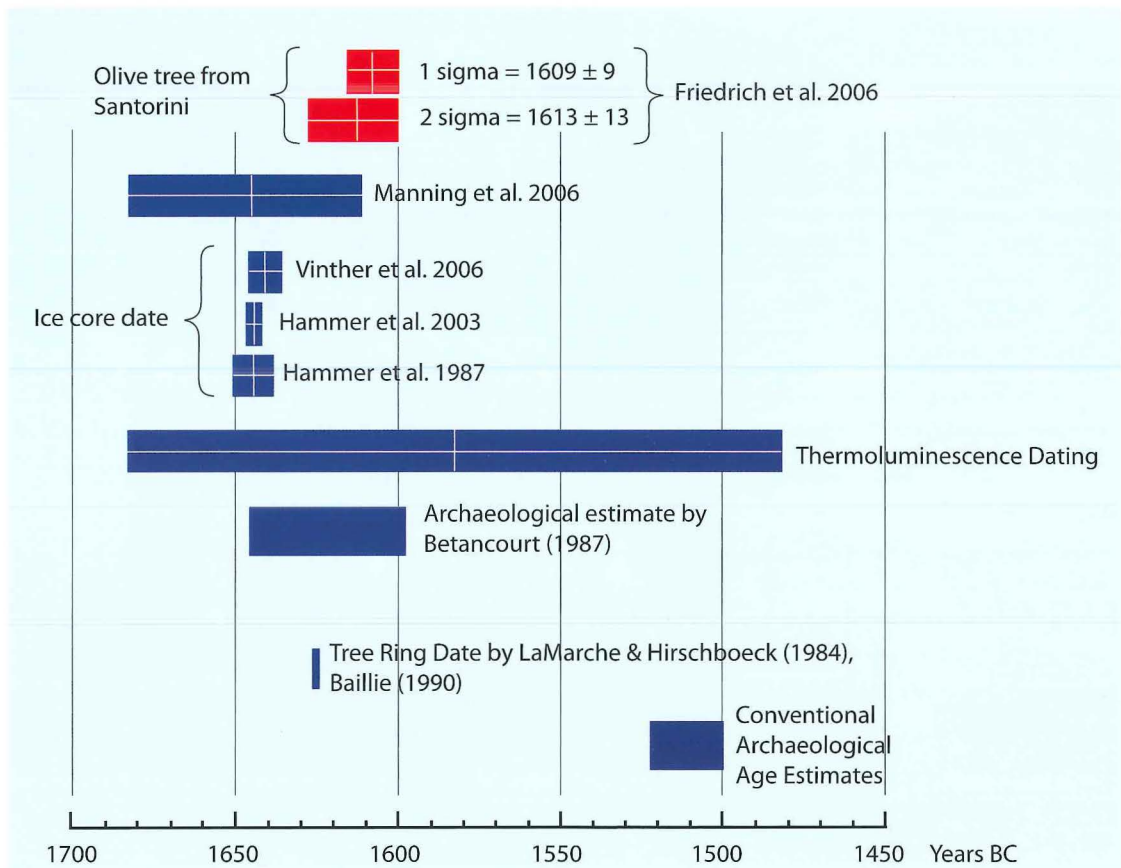


Fig. 11. The diagram shows the discrepancy between archaeological estimates and geochronological dating of the Minoan eruption. Our date for the Minoan eruption gives 1613 ± 13 cal BC, which is the most direct and precise result to date.

southwest, over the volcanic Kameni Islands to the Kolumbos volcano. Both the crater of the Minoan eruption and the CO_2 sources on the Kolumbos and Kameni fault lines are located within this zone (Friedrich & Heinemeier this volume, p. 57, Fig. 3).

The above mentioned long period of inactivity can be demonstrated directly at the growth-site of the olive tree and in the Akrotiri excavation and the site in Potamos vally (Fig. 10). The Akrotiri radiocarbon samples studied were obtained from this excavation.

The location where the radiocarbon dated olive-tree was buried alive by the pumice of the eruption is on a steep caldera wall, 150 metres above sea level. It was found *in situ* with roots and branches, and with leaves lying at the foot of the tree. The thick soil, consisting of deeply weathered volcanic tuff, in which it grew, testifies to a long period, probably

several millennia, of volcanic inactivity prior to the eruption. Since the form of Santorini in the Bronze Age was similar to that of today, with a water-filled caldera and a small island in the middle, the olive tree grew on an elevated site at least 3.5 km away from the active zone (Friedrich & Heinemeier this volume, 57 Fig. 3), thus out of range of old CO_2 , which is heavier than air and therefore tends to accumulate in low-lying areas. Strong evidence that our tree sample was not affected by volcanic CO_2 is that it would then have been impossible to match the measured ^{14}C sequence to any part of the calibration curve. We observe a downward slope in our dating sequence, whereas one would expect an upward slope if the eruption took place around 1500 BC and had been contaminated with volcanic CO_2 . The ageing effect should, if anything, increase due to increased emission in the period up to the eruption.

The pre-eruption quiescence is a crucial observation, and, together with the elevated growth-site of the trees and their distance from the active volcanic zone, it makes any significant volcanic effect on the radiocarbon dates highly unlikely.

It is curious that the radiocarbon dates proposed for organic materials from the Austrian excavations at Tell el-Dab^a seem to show an offset of more than a century (according to Walter Kutschera)¹³ or even two (according to Hendrik Bruins)¹⁴ in comparison with the dates proposed by the excavators, based on their interpretation of the archaeological material. This is roughly in line with the alleged discrepancy between our proposed date for the Minoan eruption of Santorini and the lower dates proposed for that same event based on archaeological material. Yet in the Nile Delta the possible effect of old volcanic CO₂ can be ruled out and another explanation sought. This has hitherto not been found. Instead, controlled radiocarbon datings by the laboratories at Oxford and Vienna of reliably dated archaeological material from Egyptian sources of the second millennium BC seem to correspond to dates proposed based on historical methods.¹⁵

Conclusion

The new radiocarbon date has the advantage over the results of other scientific dating methods (Fig. 11) that it is directly connected to the Minoan eruption, whereas *e.g.* the ice core date¹⁶ or the frost damage in tree ring anomalies¹⁷ are not necessarily connected to the event. It is certainly noteworthy,

however, that as early as 1984 when essentially no one was arguing for a date for the Minoan eruption of Santorini in the 17th century BC, that on the basis of their frost ring evidence, LaMarche and Hirschboeck proposed that Thera may have erupted in 1627 BC or one or two years earlier, *i.e.* within the 2 σ range of the present radiocarbon date.¹⁸ Inherently, a dendrochronological date is more precise – *i.e.* confined to a tighter time interval – than even a wiggle-match radiocarbon date because of the high replication of trees covering a given period and also the fact that absolute radiocarbon dating depends on dendrochronology for calibration. However, frost damage on tree rings is the result of a climatic anomaly that can be triggered by many processes. It is not necessarily connected to a volcanic eruption. The large error margins of the thermoluminescence method mean that it is not really relevant. Furthermore, the precision achieved by relying on a time sequence of four sequences of tree-rings far outweighs the value of a date derived from short-lived material. We therefore consider our radiocarbon date based on the 72 growth rings of an olive branch buried alive in the pumice on Thera to be the most reliable and accurate date of the Minoan eruption.

¹³ Bietak & Höflmayer 2003, fig. 1.

¹⁴ Bruins *et al.* 2008.

¹⁵ Marcus *et al.* n.d., Walter Kutschera (pers. comm. to the editor).

¹⁶ Vinther *et al.* 2008.

¹⁷ Baillie 1990.

¹⁸ LaMarche & Hirschboeck 1984.

