Dating of the Thera/Santorini volcanic eruption

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Zusammenfassung

Seit über 30 Jahren wird über das korrekte Alter des Vulkanausbruchs von Thera/Santorini debattiert. In der gegenwärtigen Diskussion, die hauptsächlich durch Archäologen und Naturwissenschaftler geführt wird, tritt insbesondere die Diskrepanz von etwa 100 Jahren für die absolute Altersbestimmung hervor. Der vorliegende Artikel beschreibt die Anstrengungen, den Ausbruch von Santorini mit naturwissenschaftlichen Methoden zu datieren, wobei auch auf die Ergebnisse der archäologischen und historischen Analysen Bezug genommen wird. Obwohl zahlreiche Literaturhinweise angegeben werden, konnte nicht auf alle Artikel und Diskussionen, die im Laufe der Jahre zu diesem Thema publiziert wurden, eingegangen werden. Statt dessen wurde versucht, repräsentative Literaturquellen zu diskutieren und aufzuzeigen, welche naturwissenschaftlichen Methoden möglicherweise zur Lösung dieses Problems beitragen könnten.

Summary

The debate about the correct date of the Thera/Santorini volcanic eruption has now been going on for more than thirty years. Today in 2012, it is largely polarized between archaeologists and scientists, who disagree on the absolute date by about 100 years. This paper gives primarily a summary of efforts to date the Santorini eruption by methods derived from the natural sciences, also referring to the results of archaeological and historical analyses. Although a rather extensive bibliography is included in this paper, it cannot possibly cover all the many papers and discussions published on this issue over the years. Rather, an attempt has been made to discuss representative sources from the literature, and to indicate some future scientific methods which may help to solve the problem.

Introduction

The volcanic eruption of Thera/Santorini (hereafter the »Santorini eruption«) in the middle of the second millennium B. C. was a truly cataclysmic event. The magnitude of the Santorini eruption is nowadays estimated to be comparable to the largest known historical eruption of Tambora in 1815 A. D., and at least as large as the famous Krakatao eruption in 1883 A. D. (Sigurdsson et al. 2006). The eruption left both regional and global traces of volcanic tephra. Neutron activation analysis, which can identify up to 20 elements in volcanic tephra, has been used to fingerprint different volcanic eruptions in the Eastern Mediterranean, allowing one to distinguish Santorini deposits from those of other volcanos in this region (Steinhauser et al. 2006; Sterba et al. 2009).

Archaeologists, who try to synchronize civilisations in the East Mediterranean in the Late Bronze Age, use the Santorini eruption as a welcome time beacon. However, in order to get an absolute date for the eruption, they need a link to the historical chronology of Egypt which provides an absolute time scale. This, then, can be compared with the result of different scientific methods. It is well known that a consensus for the eruption date between archaeological and scientific methods has not yet been reached (Fig. 1; Tab. 1).

In particular, radiocarbon dating yields an eruption date 100 to 150 years older[1] as compared to the one favoured by recent archaeological reasoning[2]. The former is usually referred to as »high chronology« whereas the latter is called »low chronology«. It is interesting to note that 25 years ago some archaeologist also argued for the high chronology (Betancour 1987), only to be immediately contradicted by the ones favouring the low chronology (Warren 1987). Different opinions about the eruption date of Santorini still persist today, despite great efforts on both sides to solve the problem (Balter 2006; Bruins 2010).

Sometimes a general scepticism about the reliability of scientific methods, and in particular radiocarbon dating, is expressed by Aegean prehistorians (Wiener 2009), triggering lively discussions of proponents from both »cultures« (Wiener et al. 2009). A strong boost for both scientific and historical time scales was recently obtained from an extensive comparison of radiocarbon dates from samples directly linked to the historical chronology of Ancient Egypt (Bronk Ramsey et al. 2010). It resulted in a generally good agreement between the two absolute time scales for the dynastic periods in Egypt. This investigation included also a slight offset of radiocarbon dates to older ages (19 ± 5 radiocarbon years), caused by the concurrence of the minimum of the seasonal variation of ^{14}C in the atmosphere with the late growing period in Egypt (Dee et al. 2010).

It should be pointed out, however, that despite the obvious success of radiocarbon dating, there is an intrinsic limi-

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[1] Friedrich et al. 2006; Manning et al. 2006; Bruins et al. 2009.

[2] Bietak/Höflmayer 2007; Warren 2009; Wiener 2009.

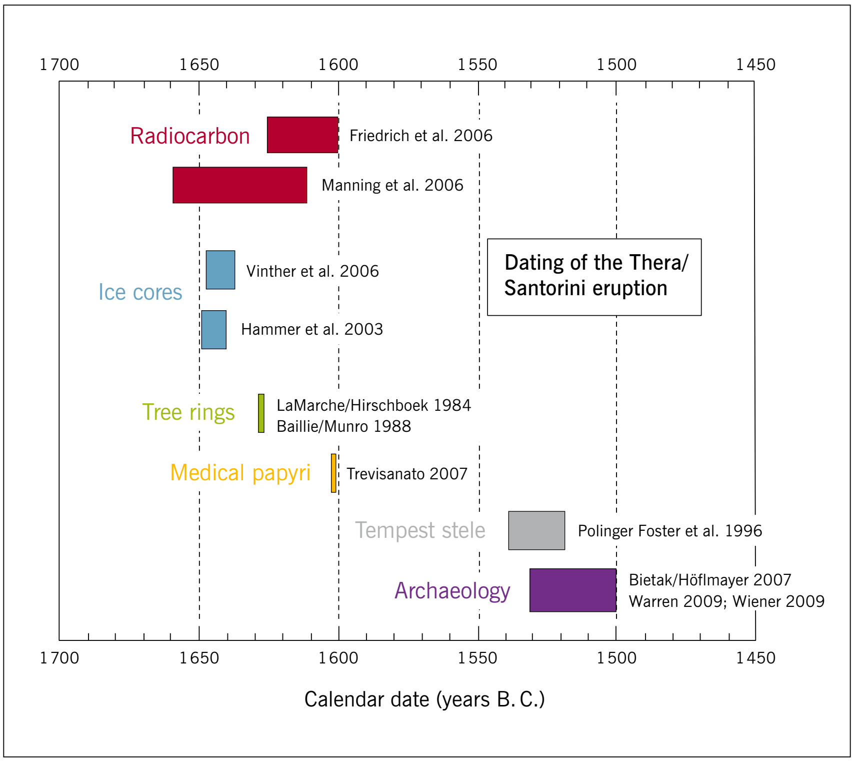

Fig. 1 Graphic summary of the efforts to date the Santorini eruption. The bars indicate the range of dates for the respective method and the given references. Numerical values for the dating ranges are listed in Table 1.

tation for the precision of absolute dates due to the »wiggles« in the calibration curve (e.g. Guilderson et al. 2005). A reduction of the uncertainty can only be achieved if a sequence of samples is available. One can then introduce so-called *a priori* conditions, i.e. reasonable assumption about the chronological order of a sequence. Then, by applying the method of Bayesian analysis (Bronk Ramsey 2009; Bronk Ramsey 2009a), one can greatly reduce the uncertainty of calibrated dates (by up to a factor of 10). Such a process is most obvious if a sequence of tree-rings can be identified of the object to be dated, e.g. for the olive tree branch buried by Santorini tephra (Friedrich et al. 2006). In general, though, the *a priori* assumptions may be less straightforward, but are necessary to arrive at the greatly reduced uncertainties in the radiocarbon results mentioned above (Manning et al. 2006; Bronk Ramsey et al. 2010). It has also been noted that the choice of the *a priori* functional form in a Baysian analysis of radiocarbon dates needs to be carefully evaluated, because it may otherwise generate unwanted effects (Steier et al. 2001; Weninger et al. 2010).

Since the need for a calibration curve in radiocarbon dating (Reimer et al. 2009) increases the uncertainty of the measured ^{14}C content substantially, one may wonder why it cannot be avoided. The reason is that for an absolute age determination without calibration, one would have to be able to measure the ratio of the parent ^{14}C to the accumulated decay product ^{14}N* (the * means that it is radiogenic nitrogen). This, however, is quite impossible to do, since the minute fraction of radiogenic ^{14}N* stemming from the ^{14}C decay is usually overwhelmed by the omnipresent ^{14}N (e.g. our atmosphere consists of 78 % nitrogen, of which 99,6 % is the isotope ^{14}N). Therefore, in ^{14}C dating only the decrease of the initial ^{14}C content is measured and an age determination depends on knowing this initial content. This requires the use of a calibration curve with its associated problems mentioned above. There has been one report on discussing a possible method for absolute ^{14}C dating (Szabo et al. 1998), but so far it has not been further pursued.

Different scientific methods should agree with each other within their respective uncertainties if they are gauging the same event. Most precise dates (within a few years) on a volcanic eruption are principally obtainable from climatic effects in tree rings (LaMarche/Hirschboek 1984; Baillie/Munro 1988), and from sulphuric acid peaks and tephra deposits in Greenland ice cores[3]. However, these are secondary effects of an eruption, and they are complicated by conditions difficult to assess such as global versus regional climatic effects in tree rings, and the identification of the signatures in ice as belonging unambiguously to the Santorini eruption. The latter difficulty is exemplified by the work of G. A. Zielinski and M. S. Germani (1998), who challenged a Santorini origin for the 1620s B.C. from the analysis of a 1623 ± 36 years B.C. sulphuric acid and volcanic glass layer of the GISP 2 ice core from Greenland. This conclusion was rejected by S. W. Manning (1998) in a response to the paper, but was followed by a defence of the original conclusion by G. A. Zielinski and M. S. Germani (1998a). A similarly controversial discussion evolved after the work of C. U. Hammer et al. (2003), who assigned volcanic glass recovered from the 1645 ± 4 years B.C. ash layer in the Greenland GRIP ice core to the Santorini eruption. In contrast, N. J. G. Pearce et al. (2004) argued that the elemental composition of this tephra

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[3] Hammer et al. 1987; Hammer et al. 2003; Vinther et al. 2006.

Tab. 1 Summary of the efforts to date the eruption of Santorini (see also Fig. 1).

Date (years B. C.)	Method	Reference
1627–1600	Radiocarbon	Friedrich 2006
1659–1612	Radiocarbon	Manning et al. 2006
1645 ± 4	Ice core	Hammer et al. 2003
1642 ± 5	Ice core	Vinther et al. 2006
1628–1626	Tree rings	LaMarche/Hirschboek 1984
1628–1626	Tree rings	Baillie/Munro 1988
1603–1601	Medical papyri	Trevisanato 2007
1539–1517	Ahmose tempest stele	Polinger Foster et al. 1996
1530–1500	Archaeology	Bietak/Höflmayer 2007 Warren 2009 Wiener 2009

deposit resemble more closely those of tephra from the Aniakchak volcanic eruption in Alaska, which happened approximately at the same time. Later the extensive work of B. M. Vinther et al. (2006) synchronizing three different Greenland ice cores (Dye-3, GRIP, NGRIP) again argued for a tephra layer from Santorini at 1642 ± 5 years B. C. This was refuted by J. S. Denton and N. J. G. Pearce (2008) with their Aniakchak hypothesis, but turned around again by a response of B. M. Vinther et al. (2008) confirming their original statement. The whole discussion got a new twist, when M. G. L. Baillie (2008) sparked a discussion about the correctness of the ice-core timescale. M. G. L. Baillie (2010) argued that the ice-core timescale should be shifted by several years in order to synchronize volcanic events including Santorini which show up in both tree-ring and ice-core archives.

Recently, records in stalagmites (S concentration, stable isotope ratios of H, C, O, and trace element concentrations) are also put forward as another indirect means of recording volcanic events including the one of Santorini (Frisia et al. 2008; Siklósy et al. 2009). One has to see whether these observations, which also seem to support a Santorini eruption date in the second half of the 17th century B. C., eventually evolve into a more firm identification.

Finally, one wonders why such a cataclysmic event as the Santorini eruption should not have been recorded in some historical writings. One hint in this direction is the so-called Tempest Stele of Ahmose, which may actually describe the eruption (Polinger Foster et al. 1996; cf. also Quack in the present volume). If this interpretation is correct, it would put the eruption date at about 1530 B. C. within the reign of Ahmose, the first king of the 18th dynasty in Egypt. This is not compatible with the results of the scientific methods, which point to the second half of the 17th century B. C., but supports the low chronology (Fig. 1). On the other hand, an intriguing analysis of (historical) medical papyri by S. I. Trevisanato (2007), describing ailments possibly caused by side effects of the Santorini eruption, date the eruption to 1603–1601 B. C. This lies within the time range of the most precise radiocarbon date from the olive tree (Friedrich et al. 2006).

Overall, one has not reached a consensus on the date of the Santorini eruption, with a particularly strong disagreement between the average of the scientific methods (second half of the 17th century B. C.) and the archaeological proponents of a late eruption date (end of the 16th century B. C.). In such a situation it would be most welcome to use other, independent dating methods, preferable ones which allow a direct dating of the eruption. In the following we will briefly discuss these methods, which, in principle, could meet this condition.

Potassium-Argon dating

Due to the very long half-life of ^{40}K ($t_{1/2}$ = 1,28 x 10^9 years), the decay of ^{40}K to ^{40}Ar* (radiogenic argon) is widely used as a radioactive clock in geochronology. Since argon is likely to be released from molten rocks setting the clock to zero, the method is particularly well suited to date volcanic events where this condition is met. It is important to note, that in potassium-argon dating the age is determined from measuring the ratio of the parent (^{40}K) to the daughter (radiogenic ^{40}Ar*), which gives an absolute date without calibration. In contrast, such an absolute age determination cannot be performed with ^{14}C (see discussion above).

Over the years, the classical potassium-argon method has been improved by measuring the potassium content through a quantitative conversion of ^{39}K (one of the stable isotopes of potassium) to ^{39}Ar via the ^{39}K(n, p)^{39}Ar reaction in a nuclear reactor. This allows one to determine both the potassium content and the decay product ^{40}Ar through a ^{40}Ar/^{39}Ar ratio measurement, greatly improving the precision of age determination. A famous example is the age of the Chicxulub crater in Mexico, which was measured to be (64,98 + 0,05) x 106 years (Swisher III et al. 1992), supporting the theory that a massive meteorite impact possibly caused the extinction of the dinosaur at the Cretaceous-Tertiary boundary time (Alvarez et al. 1980).

An interesting measurement of some relevance to the Santorini eruption was performed by Renne et al. (1997), who used the ^{40}Ar/^{39}Ar method to date the Vesuvius eruption of 79 A. D. Although the precision for such a relatively

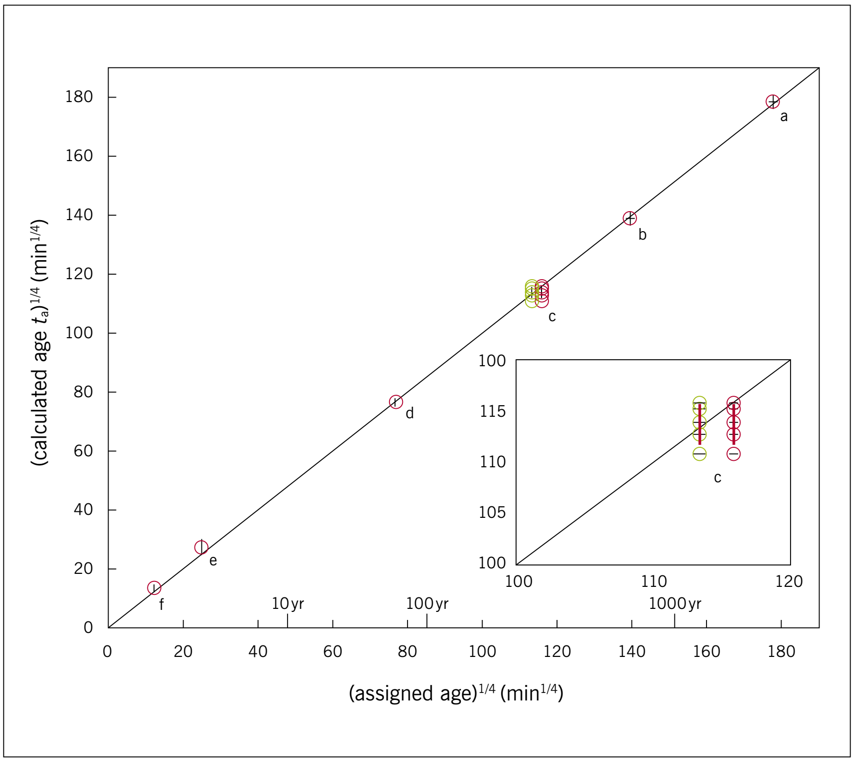

Fig. 2 Comparison of ages calculated from measurements with the RHX methods and historically assigned ages of fired-clay bricks and tile samples (Wilson et al. 2009, Fig. 4). The oldest sample (a) is a Roman *opus spicatum* clay paving brick with an assigned age of 50–160 A. D. The $t^{1/4}$ dependence of the water uptake seems to be born out quite well for the last 2000 years. For details of the RHX measurements, consult Wilson et al. (2009).

recent period was relatively poor (± 94 years), the basic accuracy of the date range proved to be correct. Since the Santorini eruption happened about 1600 years earlier, allowing for a stronger build-up of a ^{40}Ar* signal, a more precise ^{40}Ar/^{39}Ar date may be expected. Unfortunately, tephra from the Santorini eruption does not contain the potassium-rich mineral sanidine, which was used for the dating of the Vesuvius eruption. Therefore, it remains to be seen whether some suitable mineral can be found for a ^{40}Ar/^{39}Ar dating. If this happens, one should be able to determine the date of the Santorini eruption in the most direct way.

Thermoluminescence dating (TL)

TL has been widely used in archaeology (Aitken 1985; Roberts 1997). In contrast to radiocarbon dating, it is not based on an internal radioactive clock (the ^{14}C decay), but on the accumulation of trapped electrons produced in the irradiation of solid materials by internal and environmental radioactivity. Heating of the sample releases the trapped electrons generating light emission which can be translated into an age if all factors influencing the build-up of the trapped electrons are understood. In a volcanic eruption, such electron traps can be assumed to be reset in geological materials (e. g. in quartz) due to the high temperature, thus defining the starting point of the clock in a similarly direct way as for the potassium-argon dating. However, uncertainties of TL ages measured for Aegean volcanic eruptions in the second millennium B. C. were in the order of ± 200 years (Liritzis et al. 1996), too large to make an impact on an accurate determination of the Santorini eruption. Therefore, a substantial improvement of this method to date directly eruptive material is still required.

Rehydroxilation (RHX) dating of ceramics

This relatively new method of dating fired-clay ceramics by measuring the time dependent water uptake after it was removed from the kiln, is both surprising and promising (Wilson et al. 2009). Apparently the mass of a freshly fired ceramic increases proportional to the fourth root of time ($t^{1/4}$) because of the chemical binding of water from environmental moisture. Similarly, when the ceramic is heated to around 500° C, all the water is released and the clock is set to zero. By weighing the sample before and after heating, the mass of the water uptake is determined. The rate of water uptake for a specific sample material is determined by following the weight increase of the reheated sample for some time on a microbalance. It turns out that the water uptake is such a slow process, that it is essentially independent of the environmental humidity. It is, however, temperature dependent, and the uptake rate has thus to be determined at temperatures which resemble the conditions of the object through time, which, of course, could be a source of systematic uncertainty. Wilson et al. (2009) have successfully checked the $t^{1/4}$ dependence with samples of known ages back to Roman times (Fig. 2). The uncertainty reached at this age was about ± 100 years, similar to the uncertainty of the ^{40}Ar/^{39}Ar dating of the Vesuvius eruption (Renne et al. 1997). The RHX methods still has to be verified by other laboratories, but if it turns out to be a reliable method for dating ceramics, it would have a great potential to establish absolute time lines, not only for the Santorini eruption, but also for many cultural relations in archaeological excavations where ceramics is found.

Assuming that ceramics buried in Akrotiri by Santorini tephra were heated to ~500° C in the eruption, the »water« clock was set to zero and the mass increase with time would allow one to determine the date of the eruption. It would be very interesting to see if such ceramics could be dated with RHX.

Conclusion

The summary of results displayed in Figure 1 indicate the ongoing debate about a correct date for the Santorini eruption. It is intriguing that a similar disagreement between radiocarbon and archaeological dating has also been found at the Tell el-Daba site in the Nile Delta (Kutschera et al. 2012). Although the new dating methods pointed out above currently lack the necessary precision, there is hope that the scientific methods will eventually provide an accurate and precise date of the Santorini eruption. But it is clear that a very strong scientific case must be made, as long as it remains contrary to the results stemming from a seemingly well-established archaeological interpretation of the Late Bronze Age in the East Mediterranean.

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Abbreviations

DYE 3	Ice Core Site (in the context of GISP)
GISP	Greenland Ice Sheet Project
(N)GRIP	(North) Greenland Ice Core Project

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Source of figures

1	author
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Tab. 1	author

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