The eruption within the debate about the date

Floyd W. McCoy[1]

Abstract

Basic to the debate about the date for the Minoan LBA eruption of Santorini is an understanding of the sequence of geological events that characterized the eruption, that led to and followed the explosion, as well as the possible impact of the catastrophe on surrounding cultures. Extrapolations to antiquity are based upon contemporary studies of volcanism constrained within the framework of archaeological research focused on the Bronze Age of the Mediterranean and Aegean regions. Current research on the eruption as well as on volcanic hazards is summarized as a contribution towards the development of new concepts on dating methodologies and techniques for better understanding the placement and aftermath of this calamitous event in the Late Bronze Age.

Introduction

New information from geophysical, geological and archaeological research increasingly indicate that the Minoan Late Bronze Age (LBA) eruption of Santorini (Thera) was huge – a massive eruption larger in its explosivity than any other known in the past 10,000 years. There can be little doubt that the eruption had an enormous impact on cultures throughout the southern Aegean and eastern Mediterranean regions. Yet a question remains on the date of this catastrophe and how that date corresponds to the cultural time-scale of the region. To approach that question, this paper provides a narrative of geologic events interpreted to have occurred before, during, and following the eruption, including potential consequences to the environment and its inhabitants. The goal is to provide a better perspective and framework for discussions concerning the dating problem and relevance to new dating techniques.

The debate about the date must first consider exactly what is being dated – the eruption itself, or the consequences of the eruption. The first consideration dates the exact time of the eruption as recorded by the crystallization of a mineral or the formation of volcanic glass, whereby, for example, an imprint of the earth's magnetic field might be sealed into a mineral, or an unstable isotope within mineral or glass starts to decay at a steady pace. The second consideration draws on proxy criteria, when a presumed consequence of the eruption resulted in climate change, tsunami, building damage, cultural transition, and such, both in the near and far-field regions from the eruptive centre.

That the eruption was unique in time and space is clear: no other large eruptions are known in the southern Aegean region within thousands of years prior to the Bronze Age. On Santorini, the previous large-magnitude eruption was 23,000 yBP;[2] in the

---

[1] Reviews by Alexander McBirney, Kevin Glowacki, Sherry Fox, and Stuart Dunn are appreciated. Special thanks to Christos Doumas for access to the Akrotiri archaeological site, and Joann Otineru for computer graphics. Doug Faulmann and Elizabeth Ratlift provided invaluable assistance with illustrations. Support for this research over the past decade has come from: Institute for Aegean Prehistory, Pomerance Foundation, Associated Scientists at Woods Hole, University of Hawaii, National Geographic Society, and Earthwatch. Manuscript preparation was done while the author was the Malcolm H. Wiener Visiting Professor at the Wiener Laboratory at the American School of Classical Studies at Athens (2007–2008), Senior Fulbright Scholar to Greece (2007–2008), and a Foreign Fellow of the Alexander S. Onassis Foundation (2008).

[2] Druitt *et al.* 1989.

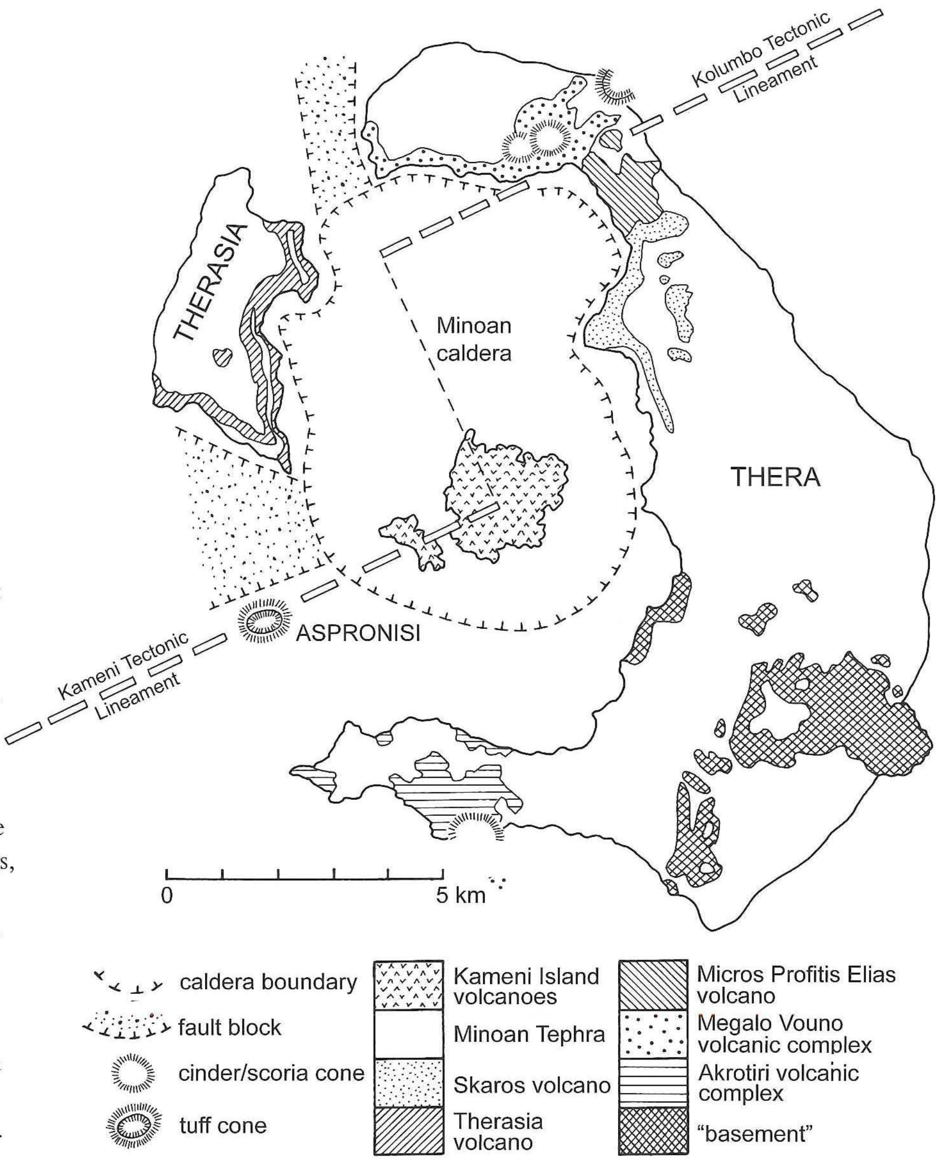

Fig. 1. Generalized geologic map of the Santorini archipelago. The outline for the Minoan caldera boundary is estimated; outlines of older caldera boundaries are not shown for clarity. Stratigraphic relationships between the rock and tephra units mapped here are presented in Fig. 3. The Kameni Tectonic Lineament continues to the southwest to Christiana Island (Sakellariou *et.al.* in press). The Kolumbo Tectonic Lineament continues to the northeast to the Kolumbo Bank underwater volcano and beyond. The offset between these two lineaments may explain the siting of the Santorini volcanic field here, in addition to other volcanic and structural features distinctive in the modern geology and topography (*e.g.*, location of the Kameni island vents, hot springs, Oia-Therasia and Gavrilos-Akrotiri fault blocks, *etc.*). Both tectonic lineaments are part of an extensive area of similar lineaments representing faults with NE-SW trends mapped on the seafloor of the southeastern Aegean Sea (Pe-Piper *et al.* 2005).

Mediterranean region the previous large eruption appears to have been the Campanian eruption from near Naples about 39,000 yBP.[3] On a global basis, it is difficult to even approximate how often eruptions with a magnitude of the LBA eruption occur because few large eruptions have occurred in historic times, in addition to the fact that geological mapping of the earth's surface is incomplete and there is the possibility that major eruptions remain unknown. Lesser eruptions with magnitudes of Krakatau in 1883 (estimated at 10x less explosive than LBA Santorini – see below) might occur perhaps once a century, whereas eruptions considered as supereruptions (+10x more explosive than LBA Santorini) might occur every 100,000 years.[4] An LBA-Santorini sized event might occur about every 100 to 100,000 years – it was simple bad luck that a geological rarity such as the Santorini eruption took place while a thriving Bronze Age culture occupied that volcanic edifice.

This paper reviews the Santorini (Thera) volcano and its Late Bronze Age (LBA) eruption in terms of: the tectonic setting of the volcano, the pre-eruption landscape, precursory tectonic and volcanic activity, major explosive activity, and poten-

---

[3] Perrota & Scarpati 2002.

[4] Decker 1990; Simkin & Siebert 2000; Mason *et al.* 2004.

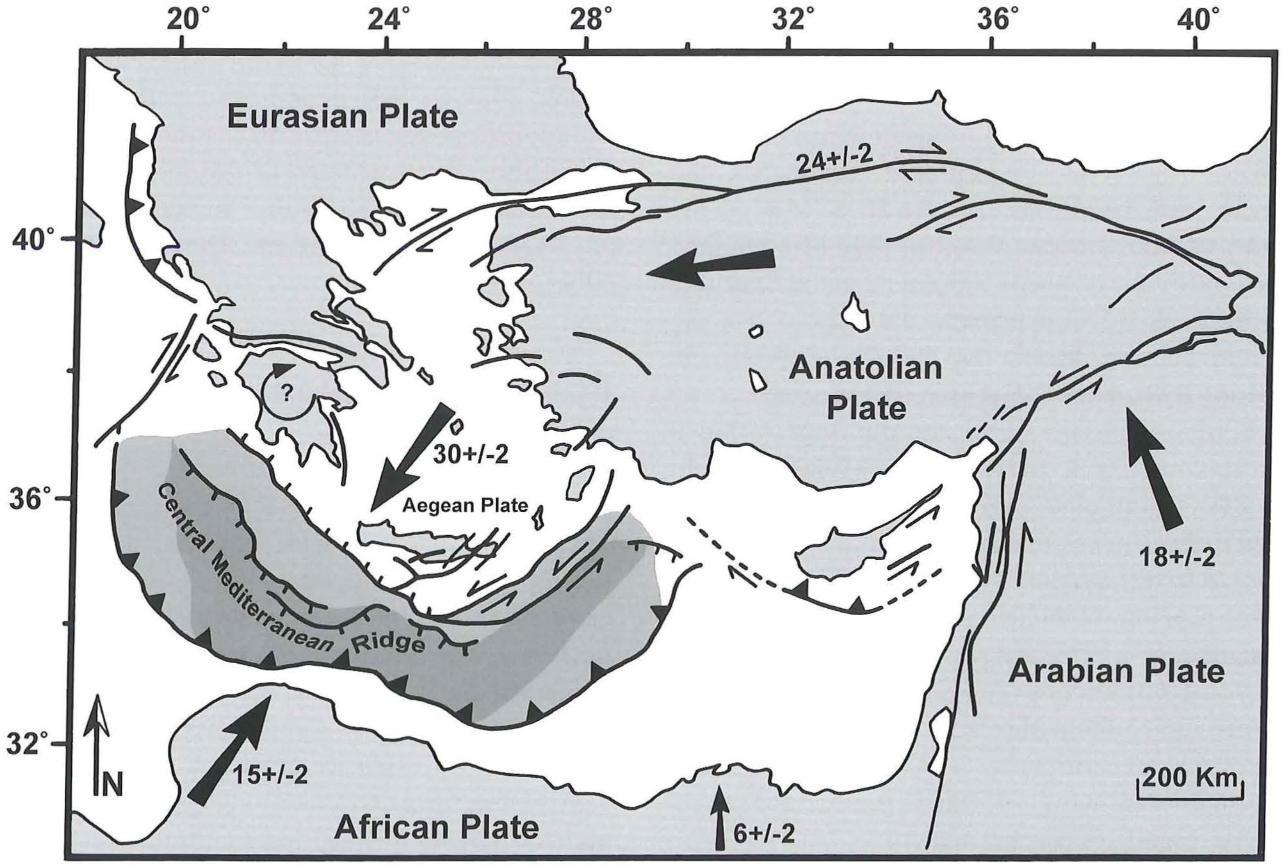

Fig. 2. The dance of the tectonic plates in the eastern Mediterranean region. Large arrows describe general plate motion; numbers identify rates of plate motion in mm/yr. Thick lines trace major faults: arrows indicate crustal motion along strike-slip faults; hatchures identify thrust faults with tick marks on the overthrust portion; large triangular hatchures mark the surface trace of major thrust and subduction by oceanic crust of the African Plate beneath the over-riding Aegean Plate; no markings along fault traces identify normal faults. Hundreds of smaller faults are not mapped for clarity. The Central Mediterranean Ridge is seafloor actively folded and deformed by the closure between the Aegean and African Plates, and it is between Cyrenaica and western Crete where the two continental crusts of the African and Eurasian Plates appear to be now in collisional contact according to geophysical data (Mascle *et al.* 1999). Figure is modified from Huguen *et al.* 2006.

tial regional consequences of the eruptive phases. The intention is to provide a summary of current research on the LBA eruption as background for critical review of dating techniques and the resulting dates, as well as for considering new approaches to the dating problem.

Tectonic setting

The arcuate alignment of volcanoes in the southern Aegean Sea, including Santorini, represent locations where molten material from depth is able to rise through major fissures in the southern Aegean crust, and erupt. Five volcanic regions or areas are defined by fissures that deviate from the arcuate trend: Susaki (northeast of the Corinth isthmus) along a fissure oriented almost E-W; Aegina, Milos, and Santorini fields, all three along fissures oriented NE – SW (for the Christiana-Santorini-Kolumbo Bank area this trend is approximately N 40-60 E [Fig. 1]); and, Kos – Nisyros fields along fissures oriented NE-SW.[5]

---

[5] Friedrich 2000; Francalanci, *et al.* 2007.

These fissures result from dilation of the southern Aegean crust, as a consequence of E-W stretching of that crust as it is pushed towards the SE and expands laterally. The push comes from the intrusion of the Anatolian plate into the northern Aegean Sea, displacing the Aegean plate to the SE at rates on the order of 3 cm/yr. (the Anatolian plate being pushed westerly by the northerly movement of the Levantine tectonic plate). Concurrently the African tectonic plate is moving directly opposite to the Aegean, in motion towards the NE at about 1.5 cm/yr.

Closure between Africa and the Aegean thus is on the order of 4 cm/yr (Fig. 2). Collision results in the Aegean plate over-riding the African plate, while the latter is plunging beneath the Aegean.[6] Ocean crust attached to the African continental crust is being subducted, although it appears that a fragment of continental Africa may now be in contact at depth with the Aegean plate below western Crete and could be the cause of the fourth to sixth centuries AD earthquake swarms ("Early Byzantine Tectonic Paroxysm" of which the AD 365 earthquake is perhaps best known).[7]

At about 100-120 km depth, partial melting of the subducting African plate produces magma that rises and feeds the southern Aegean volcanoes. Ascending magma follows whatever fissures are open at the time in response to tectonic stresses. Within this tectonic setting it appears that eruptive activity persists at any one of these volcanic fields for perhaps 3 – 4 my;[8] volcanism on Santorini commenced approximately 2 my ago during the Pliocene.[9]

This dance-of-the-tectonic-plates results in one of the most active seismic zones on earth (Fig. 2). Comparison with similar tectonic settings, such as the Sumatra-Andaman tectonic arc, finds similarities, most significantly with the relationship between tectonic seismicity and potential triggering of volcanic eruptions.[10] Marzocchi, *et al.* (2002) find a connection between great earthquakes (M>7) and large eruptions (VEI>5) in the 20th century to be statistically significant, with a time delay between seismicity and volcanism of a few years to decades and a spatial distance between earthquake site and erupting volcano of up to hundreds of kilometres. For Santorini, considering this relationship, a candidate for creating subsurface conditions possibly leading later to the LBA eruption may be the large tectonic earthquake(s) apparently at the close of the Middle Minoan IIIB period (also perhaps at the transition from the Old to New Palace period on Crete) that caused widespread damage throughout the southern Aegean region,[11] including Akrotiri on Thera (Marthari's Seismic Destruction Level [SDL]).[12]

Pre-LBA eruption landscape of Santorini

The archipelago of islands that form Santorini – Thera, Therasia, Aspronisi, Nea Kameni, Palaeo Kameni – are the topographic expression above current sea level of a volcanic field rather than a single volcano. These islands were constructed by numerous eruptions, some less explosive (Strombolian and Vulcanian eruption types) and others extraordinarily explosive (Plinean). Less explosive activity has formed modern topographic features such as Megalo Vuono, Micro Profitis Ilias, Columbo, Skaros, Akrotiri Peninsula, and the islands of Therasia, Nea Kameni, and Palaeo Kameni. All are sites of vents scattered across the volcanic field where volcanism was active for hundreds or thousands of years, producing lava flows mixed with lesser amounts of pyroclastic deposits. Some of these vents were erupting concurrently; most were not. Intervals between eruptions resulted in weathering to form soils (paleosols) and eroded landscapes. Explosive eruptions excavated craters and calderas scattered across the volcanic field that today merge into the large central caldera. Less-explosive eruptions occurred between these explosive eruptions, with current vent placement on Nea Kameni island. This eruptive history is summarized in Fig. 3.

---

[6] MacKenzie 1978; LePichon & Angelier, 1979; Angelier *et al.* 1982; Jolivet & Patriat 1999; Nyst & Thatcher 2004; ten Veen & Kleinspehn, 2003.

[7] Pirazzoli 1986; Stiros 2001; Mascle *et al.* 1999.

[8] Pe-Piper & Piper 2007.

[9] Druitt *et al.* 1989.

[10] Walter & Amelung 2007; Papadopoulos *et al.* 2008.

[11] Rehak & Younger 1998; Driessen & Macdonald 1997.

[12] Marthari 1990.

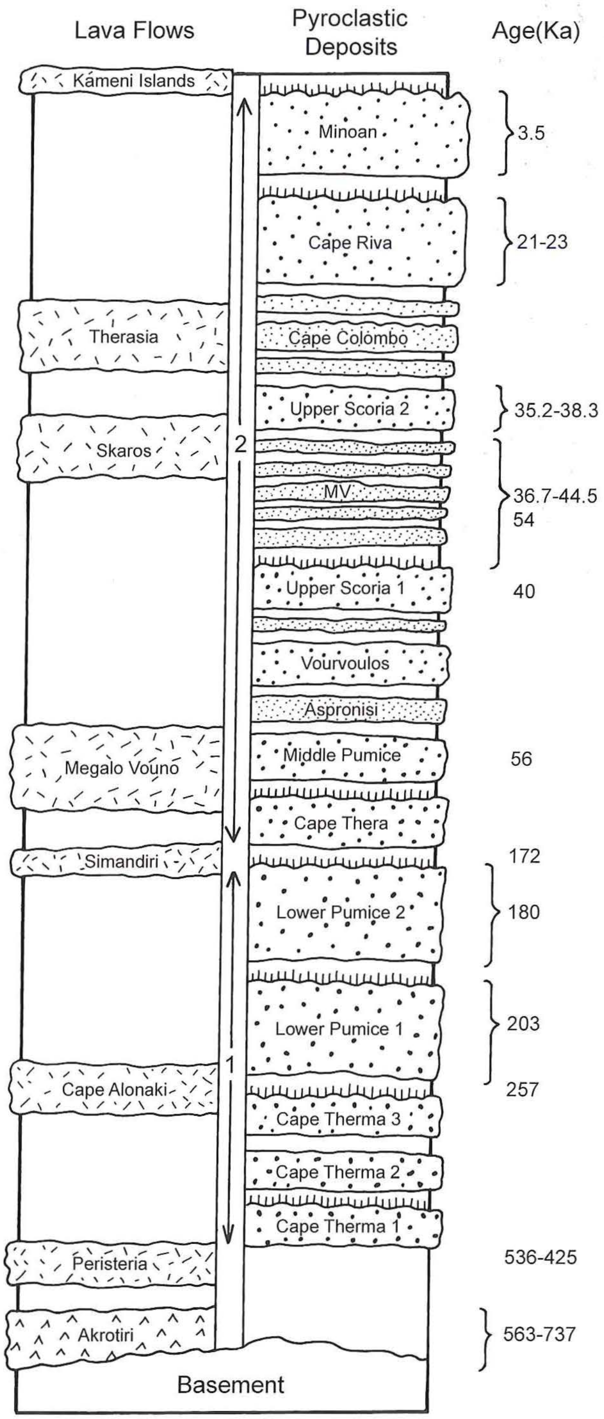

Fig. 3. Diagrammatic stratigraphic section of eruption deposits exposed in the Santorini archipelago. Relative thicknesses of deposits are approximately proportional to average thicknesses in exposures. For pyroclastic units, Plinian explosive eruptions are shown with coarse dotted pattern; lesser explosive eruption deposits are depicted with fine dotted pattern. Thin tephra layers between the Vourvoulos and Cape Riva are diagrammatic and do not represent the actual number of eruption deposits that occur within these intervals; data are from Vespa, *et al.* (2006). "MV" indicates the Megalo Vouno cinder-cone deposits, which are poorly dated and arbitrarily placed here. Few thin tephra layers down-section of the Vourvoulos deposit reflect the lack of detailed geological mapping of this portion of the section, rather than the absence of such deposits. Undulating lines along the upper contact of pyroclastic units with short vertical lines indicate erosional unconformities with palaeosols (the upper contacts of all units depicted here, pyroclastics and lava flows, are erosional unconformities). Lava flows indicate major shield-building phases of volcanic activity with the exception of the Akrotiri volcanics, which are submarine flows uplifted to form the modern Akrotiri Peninsula. The Peristeria volcanic series includes the Micro Profitis Ilias and Cape Alai volcanics. Numbers and arrows in central column outline the two cycles of volcanicity described by Druitt *et al.* 1989 for Santorini. Data and dates (in thousands of years BP) are from summaries by Druitt *et al.* 1989, 1999; Friedrich 2000; Vespa *et al.* 2006. Figure is modified from McCoy & Heiken 2000a.

It is important to understand that vent migration across this volcanic field produced individual cones and shields, coupled with repeated highly-explosive activity that re-excavated calderas. No high-conical peak has ever been constructed during the past 700,000+ years since this volcanic field appeared above sea-level. It is incorrect to extrapolate the topographic outer slopes of Thera and Therassia into mid-air above the current caldera to suggest a lofty volcanic cone, now gone.

The LBA pre-eruption landscape of Santorini can be inferred from these observations and criteria:[13]

(1) Mapping of the LBA landscape preserved today beneath the tephra layer from the LBA eruption, as exposed in cliffs, road cuts, wells, construction sites, and elsewhere on the modern landscape.

(2) Mapping of the LBA landscape buried beneath the tephra layer from the LBA eruption and

---

[13] McCoy 2005.

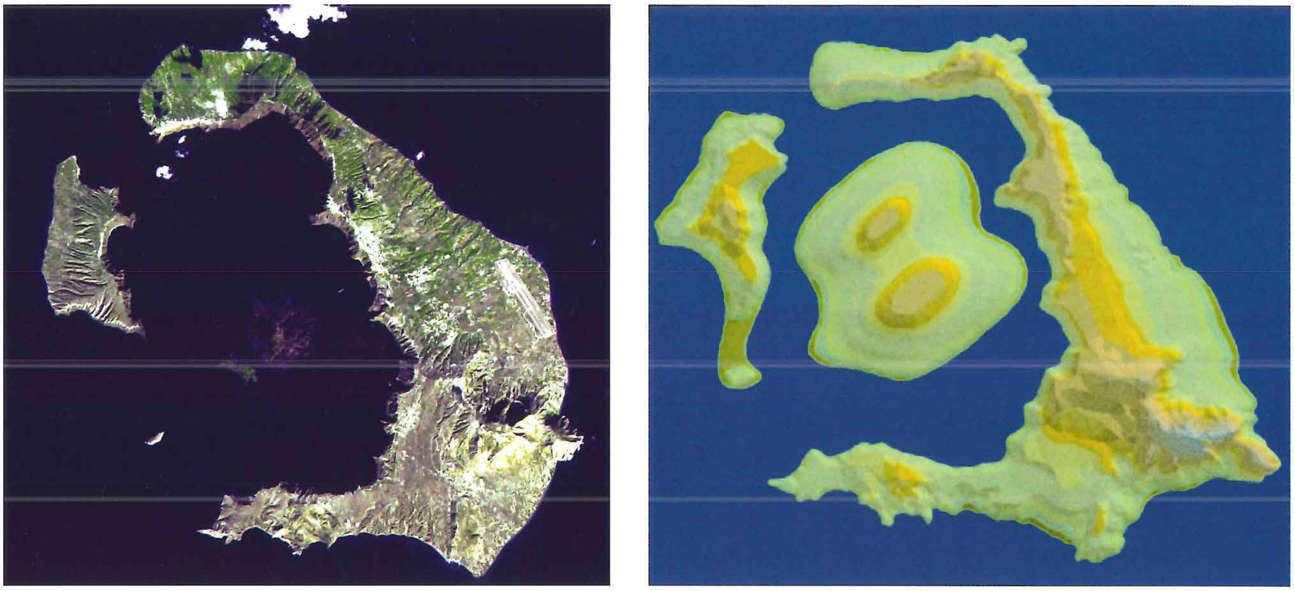

Fig. 4. (a) Present day and (b) pre-eruption LBA landscape of Santorini, both shown with the same patterns for depicting topography for easier comparisons. Shaded patterns denote 40 m contour intervals. Criteria used for this reconstruction are outlined in the text. See Friedrich 1999 for a summary of prior reconstructions of pre-eruption Santorini.

not in exposure using geophysical techniques (*e.g.*, ground-penetrating radar).[14]

(3) Inferences for the LBA landscape from pre-LBA volcanic activity and the island's tectonic setting.

(4) Inferences for the LBA landscape from emplacement and depositional mechanisms of tephra and accessory debris in the eruption deposit (*e.g.*, stromatolites).[15]

(5) Applying the rate at which the volcano grows today in constructing the Kameni islands and possible predecessor islands dated to *c.* 1350-1400 BC,[16] AD 53, 62, and 66,[17] to the interval of time, 23,000 yBP – LBA, when the volcano was rebuilding following the penultimate explosive eruption (Cape Riva eruption).

(6) Suggestions of the LBA landscape recorded on portions of the Marine Fresco from the West House, Akrotiri.

Using these criteria, a suggested pre-eruption LBA landscape is illustrated in Fig. 4. A caldera certainly existed in that ancient landscape, as first noted by Heiken & McCoy (1984), as it has through most of its entire geological history. It is inferred that the LBA caldera was nearly filled by a large island whose coastline came in close proximity to caldera cliffs. Such a depiction agrees with other published reconstructions,[18] with the only differences being the size of the central island and its topography. In the depiction shown here (Fig. 4), two peaks are shown, presuming two eruptive centres along the two tectonic lineaments (Kameni and Kolumbo lines; see Fig. 1) that seem to be offset here (which may partially explain why this volcanic field is sited here, as well as additional volcanic and structural features prominent in the modern topography).

Precursory volcanic activity

A number of observations from the Akrotiri excavation indicate that residents there had ample warning of the impending eruption.[19] It is suggested that these residents did not know they lived on a vol-

---

[14] Russell & Stasiuk 2000.

[15] Friedrich 1988.

[16] Kontaratos (pers. comm.).

[17] Guidoboni 1994.

[18] See Friedrich 2000 for a summary of these.

[19] Doumas 1983, 1990; Palyvou 2005.

cano, much less one with an extraordinary geologic history of mega-eruptions,[20] because there had been no active volcanism in the southern Aegean region (except for small phreatic eruptions on Nisyros) for hundreds, perhaps thousands of years before the Bronze Age.[21] Travellers to the west would have been familiar with erupting volcanoes in Sicily and mainland Italy, but application of that observation to the Aegean as a contemporary hazard rather than as a subject for mythology remains questionable.

Physical indicators of impending eruptions are well known and used today for predicting eruptions. Precursory phenomena may last for weeks or months, and represent the consequences of active magma intrusion within the volcanic edifice. Once intruded, usually to form magma chambers, their stability remains difficult to predict – it is unclear what triggers magma ascent from chamber to surface, and what time delay exists between intrusion and trigger. The time between intrusion and onset of the AD 1925-28 eruption on Nea Kameni appears to have been about a month (15-75 days).[22] Triggering mechanisms are not well understood but could be related to intrusions of new magma into a pre-existing magma chamber.[23]

Extrapolating precursory signals to the past suggests that Bronze Age inhabitants on Thera might have experienced some combination of the following physical phenomenon, in approximately this order, over some months prior to the eruption – any one of which likely would have been unusual and encouraged evacuation:

(1) Plants, animals, and perhaps people, suffocating in response to carbon dioxide (CO_2) accumulating in soils or topographic depressions (contemporary examples: Santorini;[24] Mt. Etna;[25] Mammoth Mountain, CA;[26] near Rome;[27] Lake Nyos, Africa[28]).

(2) Increased seismic activity of numerous small (magnitude 5, or less) earthquakes.[29]

(3) Numerous landslides off the surrounding caldera cliffs in response to the seismic activity.

(4) Uplift of the island (by a few centimetres) as magma intrudes at depth and a magma chamber fills.[30]

(5) Hot springs and fumeroles abruptly shutting off, with new springs and fumeroles appearing elsewhere, this reflecting changes in the underground magmatic plumbing system accompanying uplift of the island.

(6) Cracks opening in the ground, again in response to uplift.

(7) Increased odour of sulphur as magmatic gasses rise from the magma chamber, sulphur being particularly noticeable by an obnoxious smell.[31]

(8) Tremor, perhaps even persistent shaking, accompanying the final ascent of magma through the conduit (dike) leading to the surface, a consequence of friction on conduit walls and possible shear within the viscous silica-rich magma.[32]

The precursor eruption.

These signals can be subtle and barely felt, or strong and damaging with regional impact. As is characteristic of precursory signals today, not all of these may have occurred, nor in the order inferred above. Seismic activity is the consequence of much of this activity, related to magma movement in the subsurface and the formation of a magma chamber (including new evidence that such chambers can themselves move – it appears the magma chamber beneath Vesuvius may have migrated upwards some 4 km, to 8 km depths, between the AD 79 – 1944 eruptions and as much as 11 km over the past 20,000 years).[33] While earthquake magnitudes can be high and damaging, most, such as tremor, are of low magnitudes (M>2 or 3). The combination of their frequency – hundreds a day – and gener-

---

[20] Heiken & McCoy 1990; McCoy 2003.

[21] Fytikas *et al.*, 1976.

[22] Martin *et al.* 2008.

[23] Druitt *et al.* 1999.

[24] Barbari & Carapezza 1994.

[25] Gurrieri *et al.* 2008.

[26] McGee & Gerlach 1998.

[27] Carapezza *et al.* 2003.

[28] Baxter & Kapila 1989.

[29] For contemporary applications to eruption forecasting, see McNutt 2000.

[30] Contemporary application to eruption forecasting is discussed in Murray *et al.* 2000.

[31] See Stix & Gaonac'h, 2000.

[32] Gilbert & Lane, 2008; Tuffen *et al.* 2008.

[33] Scaillet *et al.* 2008.

ally shallow origin distinguish them from tectonic earthquakes (their seismic signals are very characteristic, and used today in eruption forecasting).

Tremor can be the final signal of an impending eruption, even for viscous magmas such as the rhyodacites of the LBA magma. They are an announcement that magma is in transit to the surface, and can continue throughout the eruption. Magma ascent rates for explosive eruptions can be on the order of 1-3 metres per second,[34] or only a few centimetres per second.[35] For LBA Santorini, Sigurdsson *et al.* (1990) estimate a magma chamber 8 – 15 kilometres in the subsurface – thus, once tremor started, the Bronze Age inhabitants may have had only hours before a vent opened and the precursor eruption started (assuming the more rapid ascent rate).

That eruption dusted the southern end of Thera with up to 20 cm of tephra.[36] Four layers are distinguishable in this deposit, suggesting four minor eruptive phases deposited from an eruption column perhaps 10 km high, each layer following upon the previous layer without significant pause. Cioni *et al.* (2000) estimate the first layer represented perhaps a 40 minute-long event. The vent was likely somewhere on the central island; the nature of the deposit suggests some interaction with water at the vent, probably groundwater beneath the central island within the caldera. If the assumption is correct that these Bronze Age inhabitants did not know they lived on a volcano, much less what a volcano was, then this small precursor eruption certainly must have been a surprise and triggered massive evacuation.

The precursor eruption[37] preceded the main explosive phase by a few months, certainly no more than a year.[38] This seems evident by the observation that the tephra deposit is composed of loose, non-cemented ash with small pumice and rock fragments that would have been easily eroded by winter rains – there is no evidence in outcrop that this deposit has been eroded or re-deposited. Accordingly, the tephra layer did not remain exposed through a rainy season (winter) before being buried by the first phase of the main eruption. There is evidence at the Akrotiri excavation of returned inhabitants removing furniture out of houses into the streets, repairing and re-plastering buildings presumably damaged by strong tremor, and cleaning ash and pumice off the streets.[39]

It thus seems clear that some months (not years) separate the precursory phase from the main explosive phases (Fig. 5). This brief hiatus between precursor and main eruption events apparently underlies the infamous "time gap" in the eruption sequence.[40]

Main explosive activity and eruptive phases

1st Major phase (Plinian air-fall)

A large earthquake immediately preceded the first major eruption phase (Fig. 5), damaging buildings at Akrotiri[41] (this is not the SDL, but the start of the VDL [Volcanic Destruction Level]), Knossos;[42] Palaikastro,[43] Mochlos,[44] and elsewhere. While this seismic event most likely was the consequence of magma ascent and eruption, it may also be related to tectonic forces perhaps as the triggering mechanism for the massive eruption.

The main explosive phase of the eruption commenced with the rapid discharge of pumice and ash, with few rock fragments.[45] Accumulation rates are estimated to have been as much as 3cm/min, in a rain of tephra from a central eruption plume estimated to have risen more than 30 km into the stratosphere.[46] The consequent deposit was up to 11m thick on Thera, in sharp contact with the underlying precursor deposit (Fig. 5). Distribution

---

[34] Sparks 1978; Dingwell 1996.

[35] Castro & Gardner 2008.

[36] Heiken & McCoy 1990; Cioni *et al.* 2000.

[37] 'Opening phase' of Cioni *et al.*, 2000.

[38] Heiken & McCoy 1990.

[39] Doumas 1983, 1990; 2005.

[40] *E.g.*, Luce 1976; Page 1980; Panagiotaki 2007.

[41] Doumas 1990.

[42] Driessen & Macdonald 1997.

[43] MacGillivray *et al.* 1998.

[44] Soles *et al.* 1995.

[45] This is the 'rose pumice' of Vitaliano *et al.* 1990.

[46] Sparks & Wilson 1990.

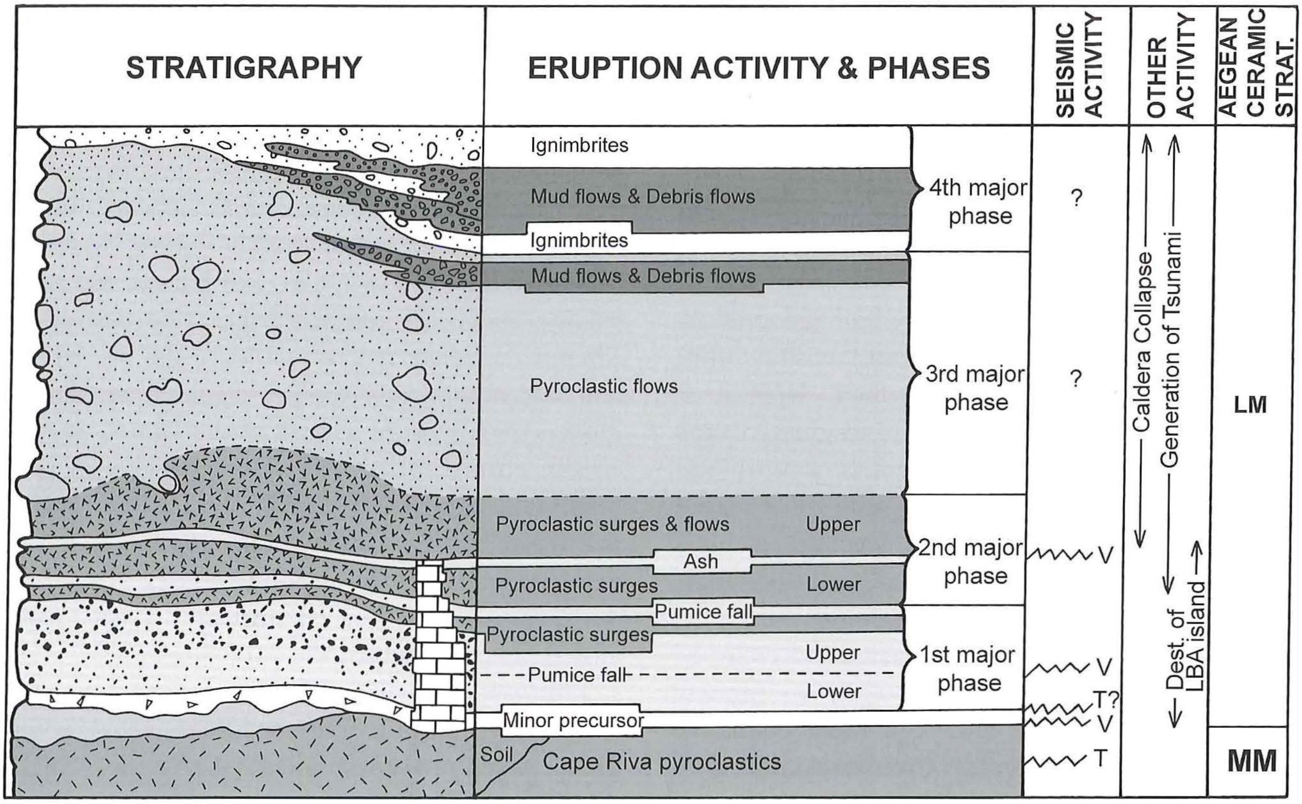

Fig. 5. Summary of the eruption in terms of: stratigraphy, volcanicity, seismicity, and suggested correlation to Aegean ceramic stratigraphy. In the tephra stratigraphy column, a solid line indicates a sharp stratigraphic contact, and a dashed line indicates a transitional stratigraphic contact; the depiction of cut-stone blocks depicts preservation and destruction levels at the Akrotiri excavation. In the Seismic Activity column, "T" = earthquake presumed of tectonic origin, "V" = earthquake presumed due to volcanic activity. In the Aegean Ceramic Stratigraphy column, MM = Middle Minoan (undifferentiated), and LM = Late Minoan IA following conventional usage.

patterns for the deposit outline a vent somewhere near the middle of the modern caldera;[47] the nature of the deposit suggests vent placement on land, likely the central island depicted in reconstructions of the pre-eruption landscape (Fig. 4).

At Akrotiri, pumice filled and preserved buildings; accumulations on roofs caused collapse, in conjunction with both tremor and other seismic activity,[48] adding to damage already done by the large earthquake following precursory activity.[49] Preserved fabrics, reeds, and other combustible materials indicate the pumice was not hot enough to burn organic debris. Pumice falling over the sea would have produced vast floating rafts of pumice.

Tephra was dispersed by atmospheric wind circulation patterns at two levels (Fig. 6), tropospheric winds at lower levels of the atmosphere and stratospheric winds at higher levels. Ash was transported as far northeast as the Black Sea and as far southeast the Nile delta (it is important to emphasize that no tephra layer has been found at the Nile Delta, rather volcanic ash occurs there in only trace amounts [<1% concentrations by volume]). Tropospheric winds distributed tephra towards the east and southeast.[50] Stratospheric winds distributed ash towards the east and northeast (Fig. 6) presumably via a southerly eddy of the jet stream. Such eddies were characteristic of 20th century regional

---

[47] Bond & Sparks 1976.

[48] McCoy & Heiken 2000a.

[49] Doumas 1990.

[50] In the pattern described by Ninkovich & Heezen 1965; Watkins *et al.* 1978; McCoy 1980; Sparks & Wilson 1990; Sewell 2001; Dunn 2002.

weather patterns during the late fall (November/December) and late spring/early summer (May/June), thus providing good indication for the time of year the eruption occurred (assuming LBA wind regimes similar to those in modern times) – late spring/early summer was suggested by McCoy and Heiken (2000a) applying additional criteria from the Akrotiri excavation.

These patterns are defined by tephra found either in distinct layers or dispersed within other sediments, and presumed to reflect dispersal of the eruption plume within the atmosphere. Eruption plumes are composed of tephra, aerosols and gasses. Tephra particles (mainly ash) are removed from the cloud via gravitational settling, leaving a plume composed of aerosols and gasses to circulate for as much as a year or two longer. Proximal patterns for eruptions of this magnitude may be more affected by atmospheric dynamics (gravity and rotational forces) and, to a lesser effect, by eruptive mechanisms, rather than wind circulation patterns.[51]

2nd Major phase (Pyroclastic surges and flows)

A dramatic change in the explosivity of the eruption occurred with this and subsequent phases of the eruption: access of water into the vent lead to highly explosive activity. It appears the vent expanded towards the southwest, progressing from land into the sea. The result was hundreds of pyroclastic surges and flows in all directions from the vent, each producing enormous plumes at the flow fronts (coignimbrite clouds), which rose into the atmosphere and stratosphere to be dispersed widely also to the east and northeast (Fig. 6). Accumulation rates on Santorini are estimated to have been on the order of 3 cm/min.[52] Surges characteristically ignored topography during flow, whereas pyroclastic flows were largely confined to topographic depressions.

The deposit is characterized in outcrop by numerous thin (cm.) layers with wavy and cross-bedded sedimentary structures. The quantity and size of rock (lithic) fragments increases up-section in the layer, particularly noticeable by the red/yellow/brown staining of lithics and surrounding halos in the ash, evidence that flow temperatures were increasing (~100-300°C)[53] and that caldera collapse was underway. In the uppermost portion of the layer, lithic fragments up to 5m in diameter occur with bedding structures sagging beneath them, evidence for ballistic emplacement as caldera collapse intensified.

At Akrotiri, any structures not buried, but protruding above the pumice layer, were destroyed. There is evidence at four sectors of the site where buildings initially diverted pyroclastic flows (southeastern corner of the House of the Ladies, northeastern corner of the West House, southern part of Xeste 2, northern part of Xeste 4). This implies that these first sets of flows either did not have velocities adequate to destroy all buildings,[54] or a flow decoupling (separation) mechanism occurred such as described at Pompeii.[55]

Entry of pyroclastic flows into the sea likely created tsunami. This is assumed by analogy to modern eruptions (*e.g.*: Krakatau, 1883,[56] Montserrat 1997, 2003[57]). Given flow azimuths in all directions around the island(s), and if only a small proportion of the numerous flows did create tsunami, then dozens of tsunami wave-sets would have propagated in all directions from Thera. The large coastal plains surrounding Santorini (Therasia, Oia, Columbo, Monolithos, Kamari, Perisa, Perivolos, Akrotiri, *etc.*) were created during this phase of the eruption, and are dramatic evidence of the volume of pyroclastic flows that interacted with the sea.

3rd Major Phase (Massive pyroclastic flow[s])

Continuing caldera collapse apparently created one or two massive pyroclastic flows that incorporated huge rock fragments, some up to 20 meters in size but more often 0.5-2 metres. Bomb sag structures

---

[51] Baines *et al.* 2008.

[52] Sparks & Wilson 1990.

[53] Downey & Tarling 1984; McClelland & Thomas 1990.

[54] McCoy & Heiken 2000a.

[55] Gurioli *et al.* 2007.

[56] Self & Rampino 1981; Simkin & Fiske; 1983; Carey *et al.* 2001.

[57] Calder *et al.* 1998; Pelinovsky *et al.* 2004.

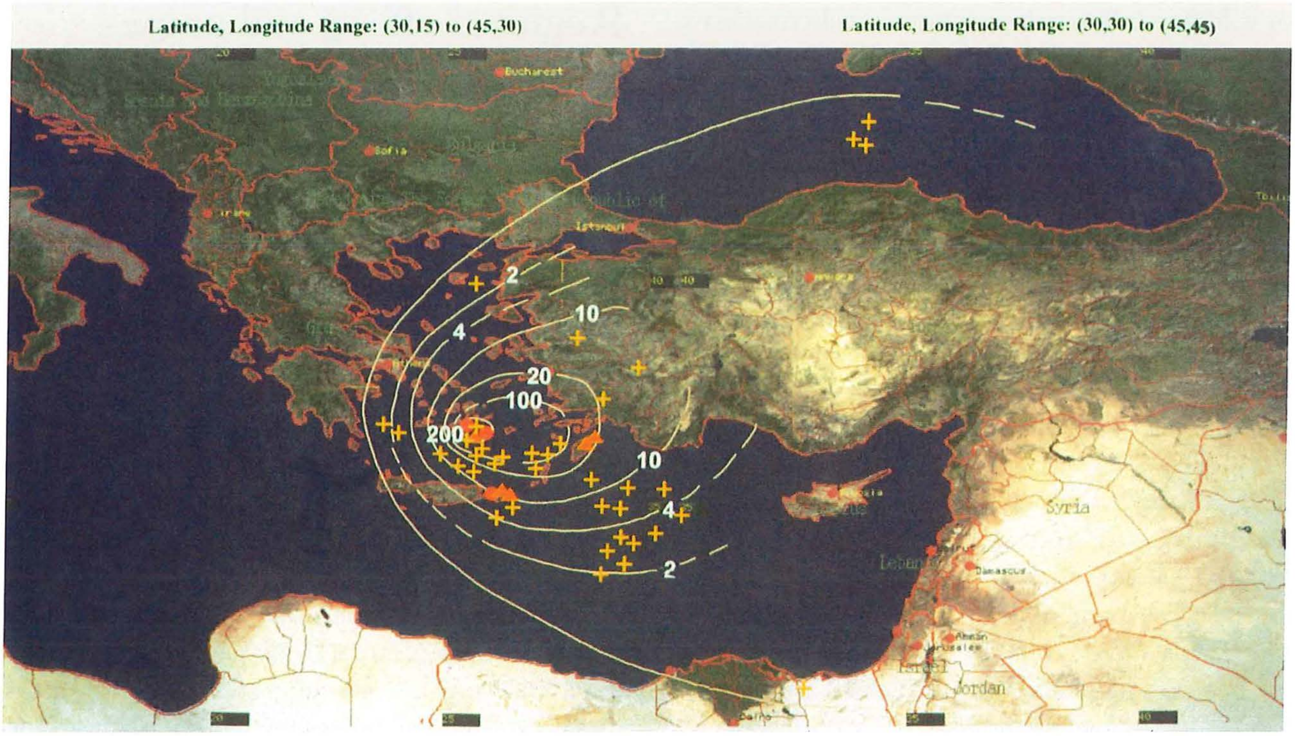

Fig. 6. Regional tephra (pumice and ash) dispersal pattern in the Aegean and Eastern Mediterranean region from the LBA eruption. Figure is modified from McCoy & Heiken 2000a and references therein; additional data from Anastasakis 2007; Sigurdsson *et al.* 2006; Roussakis 2004; and Dunn 2002. Isopachs are in cm. Sample sites are: "+" = sediment cores from the deep-sea or lakes; triangles = archaeological sites; circles = exposures on land. Such depictions are generalized to show assumed depositional conditions immediately following the eruption based upon tephra (mainly ash) thicknesses, which have been significantly modified by redepositional processes over the past *c.* 3600 years (*e.g.*, McCoy 1981; Sewell, 2001; Sigurdsson *et al.* 2006; Anastasakis 2007).

are often lacking; some of the fragments are very friable and easily broken – the implication is for a hot viscous flow that rose out of the caldera to spill through topographic lows along the caldera edge, then flow down into the sea. This deposit is up to 55 meters thick. A vague internal stratigraphic contact may indicate two flows. Temperatures of emplacement were up to 400°C.[58] The stratigraphic contact between this deposit and the underlying 2nd phase deposit is gradational, indicating no break in eruptive activity and caldera collapse.

In four settings at the Akrotiri excavation (House of the Ladies, Delta complex [two locations], and Xeste 4), large lithic fragments (1-2+m in diametre) were ballistically emplaced during 2nd and 3rd phase activity, which, upon impact, penetrated deeply into the pumice damaging buried buildings.

4th Major Phase (Pyroclastic flows, mud flows/debris flows/lahars)

The final phase of the eruption produced additional thin pyroclastic flows, much like those generated during 2nd phase activity. Apparently electrical charges on ash particles within tephra plumes both over the erupting vent[59] and where pyroclastic flows were entering the sea[60] led to rainstorms. Unconsolidated, loose, tephra mantling island slopes was mobilized by the rain and moved downslope as mud slides/debris flows/lahars (viscous slurries composed of tephra, lithics, and water, with the first two components dominant, moving as a hot

---

[58] Downey & Tarling 1984; McClelland & Thomas 1990.

[59] Thomas *et al.* 2007.

[60] Brook *et al.* 1974.

or cold flow). Downslope movement also may have been triggered by continuing seismic activity (loose tephra can amplify seismic energy).[61] The resulting deposits are obvious as layers, with thicknesses of a meter up to tens of meters, composed of rock fragments up to a few meters in size that form lag deposits from which finer material has been washed-out during flow.

Along the Akrotiri coastline, the contact of pyroclastic flows from both 3rd and 4th phase activity with the ocean led to quick chilling of the tephra, resulting in thick accumulations, that have since been eroded into sea cliffs. At least four mud slides/ debris flows/lahars were diverted to the southwest by this accumulation of tephra along the Akrotiri coastline, and directed through the area of the now-buried LBA town. Two of these eroded deeply into the accumulated tephra causing additional damage to the site, particularly in the seaward-most portion of Xeste 3 where buildings were nearly eroded to bedrock (a).[62] Accumulations of fine-grained tephra and lithics winnowed from the mud slides/ debris flows/lahars filled empty spaces within buried buildings (*e.g.*, Delta complex and House of the Ladies).

Magnitude of the eruption

The eruption was huge: new mapping and finds of tephra both on the seafloor[63] and on land[64] establish this eruption as significantly larger than previously thought, with a VEI >7.[65] Eruption magnitudes are compared by a Volcanic Explosivity Index (VEI), a numeric value estimated from the total volume of ejecta deposited during the eruption on a logarithmic scale where each value increases by ten. Comparison of the LBA eruption with notable historic eruptions: Mt. St. Helens, 1980, VEI=5.0 (the LBA eruption was 100x more explosive); Krakatau, 1883, VEI=6.0 (LBA eruption = 10x more explosive); Tambora, 1815, VEI=7.0 (LBA eruption = up to 1.5x more explosive). With an estimated total bulk volume of ejecta now up to 100km^3, or more, the eruption now may be considered as the largest known eruption in historic and late pre-historic time globally and certainly in the Mediterranean.

Regional effects and consequences of the eruption

Ash fall

The distribution of ash deposited from eruption plumes (Fig. 6) suggests a widespread distribution throughout the Eastern Mediterranean region. Significant thicknesses occurred in the southern Aegean area, including all of Crete. Inferred and mapped thicknesses on Crete may exceed 15 cm, most of which apparently was quickly eroded and re-deposited on land within depressions (such as remnants of destroyed buildings), offshore onto the seafloor, or mixed into soils.

Such accumulations on Crete likely would have caused stress to plants and animals, thus to agriculture, unless the ash was quickly eroded. Ash thicknesses of less than 1-3 meters have been found to enrich soils, especially for tree crops, whereas thicknesses in excess of that do not allow plant revival.[66] Ash coating plant leaves may reduce photosynthesis by up to 90%, but is quickly washed off by rains, as was found following the 1980 eruption of Mt. St. Helens.[67] However, ash loading of any thickness on a landscape may seriously alter ecological networks through damage to populations of micro-organisms, insects, burrowing animals, and such, possibly leading to cascading effects that could take decades to heal – critical to the re-establishment of such networks is minimal damage to vegetation and sites of refugia as seeds for re-colonization by plants and animals.[68] Ash mantling soil serves as an insulator by increasing albedo thus lowering soil temperatures, as well as by reducing water infiltration into the ground and evaporation out of soils.[69] The combination of these effects would be damaging to

---

[61] Walter *et al.* 2008.

[62] McCoy & Heiken 2000a.

[63] *E.g.*, Anastasakis 2007; Sigurdsson *et al.* 2006.

[64] Dunn & McCoy *2002*.

[65] Dunn & McCoy 2002; McCoy & Dunn 2004.

[66] Dale *et al.* 2005.

[67] Cook *et al.* 1981.

[68] Cook *et al.* 1981; Edwards 2005; Dale *et al.* 2005.

[69] Cook *et al.* 1981.

agriculture for as long as the ash remains intact and unmixed on the ground.

Problems come with toxic elements such as fluorine adsorbed onto tephra particles, and subsequently washed into water sources and soils, or ingested by livestock.[70] However, such toxic elements are present in only trace amounts in gases associated with contemporary volcanic eruptions in the southern Aegean, and it might be inferred that this was the case in antiquity. Additional problems might result from acidification of soils and surface waters by other acid volatiles adsorbed on ash particles,[71] although given the carbonate terrain of Aegean islands this might be buffered quickly.

These problems are enhanced by finer-sized ash particles. Smaller grains have larger surface areas, thus a higher surface reactivity, for scavenging volatiles from gasses in eruption plumes. Smaller grains have higher residence times in eruption plumes, and thus environmental problems may be more pronounced in distal areas of ash fall.[72] Health hazards are particularly increased through the inhalation of tiny ash particles with adsorbed cristobalite, possibly leading to lung diseases such as silicosis.[73] Finer-sized ash particles would characterize distal portions of the tephra cloud.

Pyroclastic surges and flows

Pyroclastic surges travel at considerably higher speeds than pyroclastic flows, and are damaging. Because they loose heat rapidly, they do not flow for long distances, up to 30 km at the 1980 eruption of Mt. St. Helens. Pyroclastic flows, however, can continue over long distances on land (up to 50 km or so) as well as across the surface of the ocean for some distances (30 km or more during the 161 ka eruption of the Kos Plateau Tuff;[74] up to 80 km at Krakatau in 1883).[75] Transit over water is facilitated by pumice rafts, which certainly were a consequence of the LBA eruption (see below). This raises the possibility of damage to islands and ships at sea within this distance of Santorini. Note that this would not include Crete, as suggested by Nixon.[76]

Plumes produced by turbulence and heating at the heads of active flows, or upon encountering seawater (coignimbrite clouds) would contribute fine-grained ash to eruption clouds, with potential environmental and health problems as noted above.

Pumice rafts

Extensive rafts of floating pumice certainly were adrift in the Aegean and Mediterranean Seas.[77] Pumice rafts produced during historic eruptions can be many kilometres in size (20 km across for the largest raft of many from the 1883 Krakatau eruption, which carried upright trees and skeletons of people and farm animals), many metres thick (3m for Krakatau), contain many large fragments (up to 20cm in diameter from a recent Tonga eruption), with densities adequate to walk on (500-4000 particles per m^2 in the Tonga eruption).[78] It can be assumed that numerous pumice rafts of similar dimensions occurred in the Aegean and Mediterranean Seas, and remained afloat for some years. They would have been a serious impediment to ships and shipping, as they are today.

Floating pumice that continues to be washed ashore today throughout the eastern Mediterranean, is derived from erosion of the islands in the Santorini archipelago and from reworked deposits along coastlines (it should be noted that a football-size pumice fragment can remain buoyant for up to four years before becoming saturated and sinking, and that once dried, will float again; those from the Krakatau eruption remained afloat as rafts for two years). Additional inputs of pumice during the last two centuries came from extensive quarrying operations on Thera and Therasia. Accordingly, the use of pumice in archaeological contexts as a chronostratigraphic marker for correlation to the LBA eruption must be done with extreme caution.

---

[70] Oskarsson 1980.

[71] Grattan & Gilbertson 2000; Baxter 2001.

[72] Grattan & Gilbertson, 2000; Horwell *et al.* 2003a.

[73] Horwell *et al.* 2003b.

[74] Dufek & Bergantz 2007.

[75] Carey *et al.* 1996, 2000.

[76] Nixon 1985; see also comment by Sparks 1986.

[77] McCoy & Heiken, 2000b, c.

[78] Simkin & Fiske 1983; Bryan *et al.* 2004.

Seismic activity

Volcanic eruptions are preceded, accompanied and followed by significant seismic activity. Earthquake types and patterns related to volcanism can be different from those produced by tectonic activity, in general: they tend to be locally focused near the volcano rather than producing regional shaking from tectonic motion; they occur in swarms (tremor) rather than having the tectonic signature of mainshock-aftershocks, although there can be cascading effects as swarms with tectonic earthquakes; they may be shallower in the crust (1-9 km, or so) than tectonic earthquakes; they have multi-frequency characteristics (including harmonic); and have complex focal mechanisms (rocks are breaking due to magmatic activity rather than the forces of tectonics). Seismicity related to volcanism can cause extensive damage, but usually locally within tens of kilometres of the eruption.

Earthquakes related to the LBA eruption (Fig. 5) were damaging on Santorini (as seen in damage to buildings that were being buried during 1st phase activity at Akrotiri), and farther afield perhaps as far as Crete. Modern analogies suggest only restricted damage farther than this. Tremors might also have been felt on Crete, which would have been unsettling to inhabitants. This does not deny the possible occurrence of tectonic earthquakes, and consequent damage to structures, concomitant with the eruption, given the relationship between seismic activity and volcanism[79] as well as with seismic cascading effects.[80]

Tsunami

Numerous tsunami were produced during the eruption that propagated throughout the Aegean and Mediterranean Seas. Tsunami are not single waves, but sets, or packets, of perhaps five or eight waves within which one or two are larger and potentially damaging to coastal areas (see below). Volcanogenic mechanisms for tsunami generation during the LBA eruption, based upon observations at historic eruptions,[81] include caldera collapse (2nd through 4th eruption phases), landslides off caldera walls (all eruption phases), and the entry of pyroclastic flows and mud slides/debris flows/lahars into the sea (2nd through 4th phases) (Fig. 5). These mechanisms were active during the LBA eruption, and if all were effective in tsunami generation then the seas were turbulent with numerous tsunami sets.

That tsunami were generated is clear from exposures of sedimentary deposits left from tsunami passage or inundation: Santorini;[82] Amnissos, Crete;[83] Palaikastro, Crete;[84] Western Turkey;[85] Caesarea, Israel;[86] and the deep seafloor of the central Mediterranean Sea.[87] These deposits can be difficult to distinguish from sedimentary accumulations resulting from other types of high-energy sedimentation events, such as storms, and careful study is required for interpreting them as a consequence of tsunami inundation.

Dating can use radiometric techniques on organic or carbonate debris, or from microfossil assemblages found in the deposit. The presence of pumice is often cited as evidence for, and providing a date of, tsunami inundation. This assumption may be incorrect, particularly for coastal areas some distance from Thera: as an example, whereas a tsunami wave might reach a Mediterranean coastline in 20 minutes, a pumice raft might take months to reach that same shore via slow surface currents, thus there would be no tie between tsunami generated during the LBA eruption and the deposition of pumice in a sedimentary deposit.

Given that the Minoan culture was involved in extensive maritime activities, especially trade,[88] and given the active Aegean tectonic setting and its consequent seismicity,[89] we might expect that ancient cultures in the Aegean and Mediterranean ar-

---

[79] Marzocchi *et al.* 2002; Lemarchand & Grasso 2007; Walters & Amelung 2007.

[80] Pirazzoli 1986; Nur & Cline 2000; Velasco *et al.* 2008; Marsan & Lengline 2008.

[81] Latter 1981; Beget 2000.

[82] McCoy & Heiken 2000b.

[83] Marinatos 1939; Pichler & Schiering 1977.

[84] McCoy & Papadopoulos 2001; Bruins *et al.* 2008.

[85] Minoura *et al.* 2000.

[86] Goodman per. comm.

[87] Kastens & Cita 1981; Cita *et al.* 1984; Hieke 2000.

[88] Doumas 1983; Dickinson 1994.

[89] McKenzie 1972; Papazachos 1990; Guidoboni 1994; Meier *et al.* 2004.

eas experienced frequent tsunami, much as modern cultures have,[90] and that recovery after a damaging event was readily accomplished. However, many of the Bronze Age coastal communities in the Aegean were abandoned and not rebuilt following the LBA eruption, with the Minoan culture supplanted within a few generations by the Mycenaean culture from the Greek mainland.[91] It would seem, then, that damage from tsunami was exceptional (in addition to other effects from the eruption). And that would imply that wave amplitudes, with consequent coastal inundation and run-up, also may have been exceptional.

Estimates of maximum wave heights from field observations,[92] and computer modelling[93] indicate highly variable wave amplitudes along the south coast of Ios (north of Thera) and the north and east coasts of Crete, from <1 to 26m. Variability is a function of focusing effects by tsunamigenic mechanisms during wave generation and by water-depth changes in the coastal zone where the waves come ashore, and may explain objections raised by Dominey-Howes (2004) and Pareschi *et al.* (2006) to evidence cited for tsunami generation. Coastal sites where tsunami impact is assumed must be carefully evaluated in terms of topography and bathymetry, as well as geographic position relative to tsunamigenic sources and potential focusing effects. Certainly the higher values of wave amplitudes for LBA tsunami would have been damaging to Bronze Age coastal facilities and ships in port.

It is worthwhile to briefly review tsunami characteristics, and note the misconceptions too often repeated in the professional and popular press, for a better understanding of possible impacts related to LBA activity:

A tsunami wave is not a single wave – tsunami, like most waveforms, come in groups with perhaps five or eight noticeable waves in a set.

Open-water wave heights are not noticeable – in deeper waters, tsunami wave heights are often undetectable, with amplitudes no more than wind waves. Tsunami wave amplitudes can be no more than 0.86 of the water depth.

Open-water waves interact with the deep-sea floor (wind waves do not) – in the deepest ocean depths, tsunami will stir bottom sediments.

As tsunami enter shallow water and come ashore, wave heights increase tremendously.

As tsunami come ashore, wave velocities decrease – while tsunami travel across open water at speeds of 600 km/hr., or more, they slow down tremendously (exponentially) in shallow coastal water to speeds more like 6-10 km/hr., and can be outrun (this author did that as a child).

Tsunami waveforms do not take the shape of plunging breakers (the "tube" of surfers) – they form near-vertical walls of water, a wave form known as a bore. Given the immense distances between tsunami crests (wavelength) on the order of hundreds of km, this wall represents a powerful flood of water at the level of the bore crest that comes ashore and remains for tens-of-minutes or longer.

Arrival in the coastal zone of tsunami is not always announced by the withdrawal of the ocean – wave forms are sinusoidal with crests and troughs. If the trough arrives first then there is the withdrawal, whereas if the crest arrives first there will be no withdrawal. Which arrives first is a function of the tsunamigenic mechanism.

Run-up on land, or the distance inland by flooding from tsunami inundation, cannot be calculated from wave height(s) offshore, but are suggested from the presumptive relationship that larger waves can result in longer distances of run-up (hydraulic roughness factors such as coastal morphology, topography, vegetation, buildings, *etc.*, are the determining factors).

Atmospheric effects and climate change

Climate changes produced by volcanic plumes result in heating of the lower portions of the stratosphere and cooling in the troposphere, a consequence of ash particles, aerosols and gasses in the plumes. Ash particles are removed from plumes with gravitational settling, leaving plumes composed of aerosols

---

[90] Papadopoulos & Chalkis 1984; Guidoboni & Comastri 2005.

[91] Barber 1987; Dickinson 1994; Driessen & Macdonald 1997.

[92] Pichler & Schiering 1977.

[93] McCoy *et al.* 2000; Bruins *et al.* 2008; Novikova *et al.* forth.

and gasses to circulate for as much as years following eruptions with significant climate effects.[94]

The principal volcanic gases, many forming aerosols, listed in approximately decreasing concentrations, are: water, carbon dioxide, sulphur dioxide, hydrogen chloride, hydrogen sulphide, hydrogen fluoride, and minor amounts of carbon monoxide, hydrogen, and radon.[95] High concentrations of sulphur and fluorine can be particularly lethal and lead to severe climatic changes when combined with water to form acids, with consequent stress on cultures. Additional sources of gas, particularly chlorine, comes from the evaporation of seawater when hot pyroclastic flows enter the ocean.[96] Gas compositions and concentrations may be estimated from glass or fluid inclusions in minerals and glasses, or phase equilibria considerations for minerals incorporated within the tephra. Estimates may also come from contemporary measurements of gases at volcanoes along the southern Aegean arc, including the Kameni islands at Santorini, although such extrapolations to the LBA eruption must be done with caution.

Using analyses of inclusions in glass and minerals, Sigurdsson *et al.* (1990) estimate a total yield of sulphur during the LBA eruption as intermediate between that of the Krakatau and Tambora eruptions. These two historic eruptions reduced global temperatures by up to 1.2°C for at least 3 years, with local weather perturbations, crop failures, famine, and health epidemics. Climate modifications and associated health problems equal to or perhaps surpassing those following the Tambora eruption occurred from an unknown eruption in AD 536[97] and the Huaynaputina (Peru) eruption in AD 1600.[98]

Evidence for climate change following the LBA eruption remain poor, however. The eruption came as climate in the eastern Mediterranean region was in transition from wetter and somewhat cooler conditions, to a dryer and warmer climate.[99] Brief (decadal) perturbations during this transition appear from proxy criteria in Greece and may be evidence for climate modification due to the eruption.[100] The suggested magnitude of the LBA eruption would allow for interhemispheric transport of the plume,[101] resulting in global effects.

High concentrations of fluorine gas, which when combined with water forms hydrofluoric acid, contributed to the environmental impacts associated with the 1783 Laki Fissure eruption: dry, toxic, acidic fogs and weather perturbations (colder winters, warmer summers) with consequent crop damage, health problems, and high levels of animal and human mortality.[102] It is not known what the fluorine levels were for the LBA eruption, and thus what effect acid rain may have had on LBA cultures; contemporary levels of the gas associated with southern Aegean volcanoes is low at non-toxic levels.

Additional health hazards come from fine-grained volcanic ash particles transported in eruption plumes. Smaller sizes have larger surface areas (per unit mass) that adsorb high concentrations of iron, silica (as cristobilite) and hydroxyl radicals. Additional hazards may come from tiny fibrous zeolites (*e.g.*, erionite; A. Tibaldi, pers. comm.) as accessory particles incorporated during the eruption from older hydrothermally-altered deposits. The bioreactivity of ash in lungs can cause severe health effects, inhaled both from suspended particles settling out of the eruption plume as well as from re-suspended ash on the ground[103] – similar consequences can be expected to have occurred after the LBA eruption.

The Eruption – A global and Minoan perspective

In summary, what might an inhabitant of an island in the southern Aegean region – other than Santorini – have experienced before, during, and after the LBA eruption? Some idea comes from compar-

---

[94] Robock 2000.

[95] Baxter 2001.

[96] For the LBA eruption, Sigurdsson, *et al.* 1990, estimated only a small contribution from this source, negligible compared to that derived from the erupting vent.

[97] Larsen *et al.* 2008.

[98] De Silva *et al* 2000; Verosub & Lippman 2008.

[99] McCoy 1980b; Moody *et al.* 1996.

[100] Bottema & Sarpaki, 2003; Moody forth.

[101] Baines *et al.* 2008.

[102] Stothers 1996; Grattan & Gilbertson 2000.

[103] Horwell *et al.* 2003a, b.

ing the effects and consequences of two historic eruptions of somewhat similar, although lesser, explosivity, Karakatau (1883) and Tambora (1815).[104]

Conditions for an eruption might have been established with the strong earthquake(s) during the Middle Minoan period in the Aegean (MM III; at the transition between the Old and New Palace periods on Crete; the Seismic Destruction Level at Akrotiri and elsewhere). It is presumed that this was a tectonic earthquake that, with aftershocks, may have opened cracks as conduits for magma ascent from melts deep in the crust at the subduction zone. The century or so between this earthquake and the eruption would be adequate for magma ascent of a viscous silica-rich melt to the surface.

As magma collected in a chamber approximately 8 to 15 km below Santorini, precursory activity to the impending eruption would have been felt and noticed locally, with larger earthquakes felt farther and possibly causing damage. Assuming this was a surprise to the Bronze Age inhabitants of Santorini, evacuation would have been instigated as the precursory activity intensified, then culminated in the precursory ash eruption.

Then a lull in the activity. Some apparently returned to the island, to sweep ash into piles, to repair buildings, to move furniture outside either to make space for repairs or to live outside until buildings were considered safe. Some weeks or months passed, a period without rains that would have easily eroded and removed the thin ash deposit.

And then came the major eruption. A preliminary warning of the impending explosion seems likely, perhaps sharp earthquakes and initial loud explosions as the vent opened, triggering not only the final exodus of inhabitants, but perhaps the eruption. Once at sea in deeper water, those escaping on boats would be safe from damage by tsunami, but not necessarily from pyroclastic flows if they were only a few kilometres offshore. In rapid succession, in perhaps a day to no more than a few days, the Aegean and eastern Mediterranean region might have experienced:

Deafening explosions, perhaps heard thousands of kilometres from the vent (explosions during the Krakatau eruption were heard more than 4000 km away).

An airwave that rapidly circumvented the earth multiple times (seven times during the Krakatau eruption).

Near-constant shaking of the ground with tremor, especially felt on islands nearby.

A rapidly rising plume of tephra over the vent, rising to 40 km or more, well into the stratosphere, clearly in view throughout the southern Aegean.

Darkness over the region beneath the tephra cloud, particularly proximal to Santorini, lasting for more than a day and perhaps for a few days (darkness was observed up to 600 km for two days after the Tambora eruption).

A rapidly dispersing tephra cloud, by tropospheric winds to the east and southeast reaching Anatolia in a few hours and the Nile delta in less than 10 hours (assuming surface wind speeds of 50 km/hr), and by stratospheric winds to the east and northeast reaching Anatolia in less than a hour and the Black Sea in a few hours (assuming jet stream velocities on the order of 240 km/hr).

Initially a rapid fall of pumice and ash from plumes generated over the vent and where pyroclastic flows entered the ocean, as well as from a tephra cloud downwind of the eruption. Accumulation rates on Santorini of 3+ cm/hr, filled already destroyed structures with tephra, and loaded roofs of buildings not destroyed leading to roof collapse; distal areas received a dusting of fine ash that would be quickly eroded and dispersed (during the Tambora eruption, coarser ash particles continued to fall 1 to 2 weeks after the eruption, and finer ash particles remained in the atmosphere for up to a few years, circling the globe).

Lightning and rain from electrical charges that developed within the eruption plumes, producing debris flows and lahars on Santorini, and violent rains in the southern Aegean region.

An odour of sulphur downwind of the eruption (up to 800 km downwind during the Tambora eruption).

Turmoil in the Aegean and eastern Mediter-ranean Seas from dozens of tsunami sets, produced by caldera collapse and the entry into the sea of

---

[104] Self & Rampino 1981; Stommel & Stommel 1983; Simkin & Fiske 1983; Stothers 1984; Oppenheimer 2003.

pyroclastic flows and mudflows/debris flows/lahars; along coastal areas these could cause significant damage depending upon coastal and offshore morphology.

Large rafts of floating pumice adrift in the Aegean and Mediterranean Seas, these enhancing passage of pyroclastic flows over the surface of the ocean, but inhibiting ship traffic.

Climate cooling for a few years following the eruption.

Colourful sunsets around the world for a few years (three years following Krakatau).

From Crete, the eruption would have been heard, seen, felt and smelled. From Crete and the Nile delta, the eruption would have been announced by brilliant glows toward the NW particularly at night, lightning, daytime darkness, sounds like cannon fire, and many tsunami, followed by climate modification and beautiful sunsets. To any culture in prehistoric or historic times an eruption of this magnitude would have been stunning and frightening, and certainly damaging. Equally astounding to the Aegean Bronze Age populace would have been what was left afterwards: where there had been an island with mature volcanic soils (it had been some 23,000 years since the last major eruption there), good anchorages, and established communities with some religious significance to regional cultures,[105] there was now a larger central hole filled by the sea, white and choked with floating pumice, surrounded by a smouldering pile of loose pumice, ash and rocks. The consequences were global as well. It should be the stuff of legends.

And it should have provided much for deciphering an absolute date.

---

[105] Doumas 1983; Marinatos 1984.