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The Great Minoan Eruption of Thera Volcano and the Ensuing Tsunami in the Greek Archipelago

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Abstract. The eastern Mediterranean has been the cradle of many great civilizations. The history of the area consisted of glorious battles, heroic acts, and the rise and fall of great civilizations. But, sometimes, natural hazards became the cause for a new classification of the political, as well as of the military status quo of the region. The enormous eruption of the submarine volcano at the Greek island of Thera (Santorini) during the Bronze Age, around 1500 BC, is such a natural hazard. The tsunami generated by the eruption, literally wiped out the peace-loving Minoan civilization who inhabited the island of Crete. After the sea subsided, the configuration of the area was altered, and the decline of the Minoan principality on the Archipelago began. The present paper introduces evidence concerning the tsunami and states some of the after-effects which were partly responsible for the decline of the Minoan empire. All the information is gathered from historical sources and from recent research works. An effort has been made to include many of the theories introduced by various researchers through time concerning the event. Finally, information has been included from all known research, as well as from the author's own conclusions, in order to make the paper useful to future researchers.

Key words. Bronze Age, Thera (Santorini) volcano, Minoan Crete, tsunamis, caldera.

1. Introduction

Thera (Santorini) is the most southerly island in the Cyclades archipelago in the eastern Mediterranean (Figure 1). It was once about 16 km in diameter, and before it acquired the name of Thera it had be known as Kalliste, 'the most beautiful island'. It was also called Strogili, the circular island. Today, these names are no longer appropriate as descriptions. Thera is, in fact, three fragments of what was once one island. The transformation of Thera into a caldera is the result of a great eruption, or series of eruptions, which wrecked the island around 1500 BC. For Thera is a volcano, the only active volcano in the Aegean.

There can be only a few subjects with so extensive a bibliography as the great Minoan eruption of Thera volcano. An abundance of scientists in practically every field, ancient historians, archaeologists, vulcanologists, geologists, even poets, and devoted amateurs, have concerned themselves with the volcano of Thera.

Professor S. Marinatos, Director of the Greek Archaeological Service, published

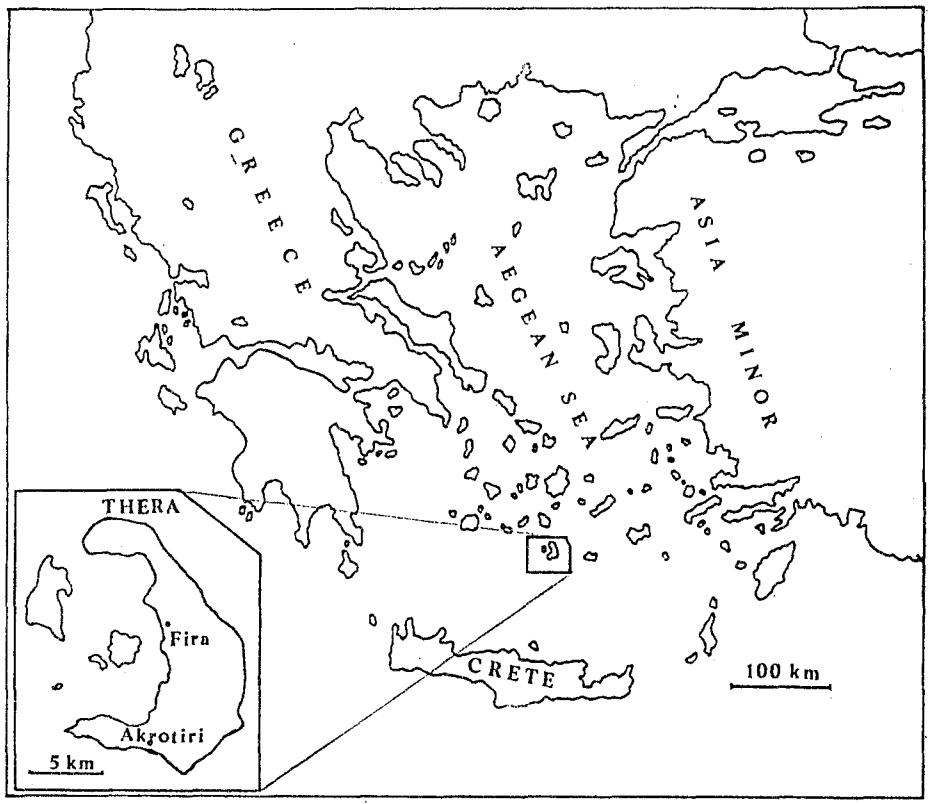


Fig. 1. The (Santorini) and its location in the Aegean Sea.

in 1939 an article entitled 'The volcanic destruction of Minoan Crete' (Marinatos, 1939). He was the first to argue that Minoan Crete was in fact volcanically destroyed. The reaction of the scientific world towards his argument may be narrowed down to the statement expressed by the editors of the English journal *Antiquity*: ". . . his Thesis requires additional support from excavation on selected sites".

In 1965, Ninkovich and Heezen, two American scientists, published evidence which scientifically reinforced the argument stated by Marinatos. In particular, they discovered that five cores of sediment from the ocean floor of the eastern Mediterranean precipitated a far-reaching reappraisal of Aegean history in the fifteenth century BC. The cores contain volcanic ash from the island of Thera, ash which was deposited over a wide area by a volcanic eruption of vast explosive power.

In 1967, Marinatos, after carrying excavations at Akrotiri near the southern end of the main island of the Thera group (Figure 1), and amplifying earlier discoveries

of sub-volcanic Minoan walls, combined with the great height of the volcanic overburden, may be said to proved much of his thesis of 1939.

My main aim is to support Marinatos' theory that a seismic wave (tsunami) was generated by the eruption at Thera during the Bronze Age and this was a major catastrophe for the island-based empire of Minoan Crete which resulted in the transference of power from the Minoans to the mainland Greeks (Mycenaeans). Personally, I favour a much earlier date for the Minoan eruption. Marinatos and most of his supporters date the great catastrophe to about 1400 BC, whereas I favor a date of about 1550 BC plus or minus 50 years. My argument is based on the principal historic evidence, which has been accumulated.

The present paper is divided into three parts. The first part contains a brief speculation of Thera's great eruption in respect to the decline of the Minoan Empire. The second part refers to the tsunami which followed the great Minoan eruption introducing evidence about its generation and its effects on Minoan Crete. The third part contains estimates of the characteristics of the tsunami, showing its destructive power.

2. The Thera Volcano Theory and the Destruction of Minoan Crete

The Greek island of Thera (Santorini) was, for many years, the battleground of ideological disputes. The great Minoan eruption of the volcano at Thera during the Bronze Age motivated many scientists to express an abundance of theories. Anything mysterious that occurred at about the same time has been connected, in one way or another, from time to time, with the volcanic eruption. The destruction of Minoan Crete, the myth of Atlantis, the crossing of the Red Sea by the Israelites, are just a few events which have been related to the eruption.

The island of Crete lies 70 miles to the south of Thera (Figure 2). During the Bronze Age, Crete was inhabited by the Minoans, named after their legendary king Minos. The Minoans dominated the Aegean, colonizing other islands and trading with the Egyptians and the Phoenicians. The expansion of Minoan influence over the Cyclades Islands dates back into the Middle Cycladic period, to 1700 BC at least, and perhaps earlier. They established the first true European civilization and built many towns and four major palaces, the most important of which was at Knossos. However, during a short time period, between 1550 and 1400 BC., the Minoan empire declined for no apparent reason tempting many scientists to connect this decline to the volcanic eruption at Thera.

As early as 1932, when he was excavating at Amnissos (Figures 2, 3, 4), Marinatos started to theorize that the destruction of the Minoan empire was an effect after of Thera' s eruption and of the resulting tsunami. In 1939, after excavations in Crete resulted in significant discoveries, Marinatos pondered about the sudden and simultaneous destruction and abandonment of so many Minoan villas and of the three palaces (except the one at Knossos) and published his famous article in the English journal *Antiquity* where he stated emphatically that

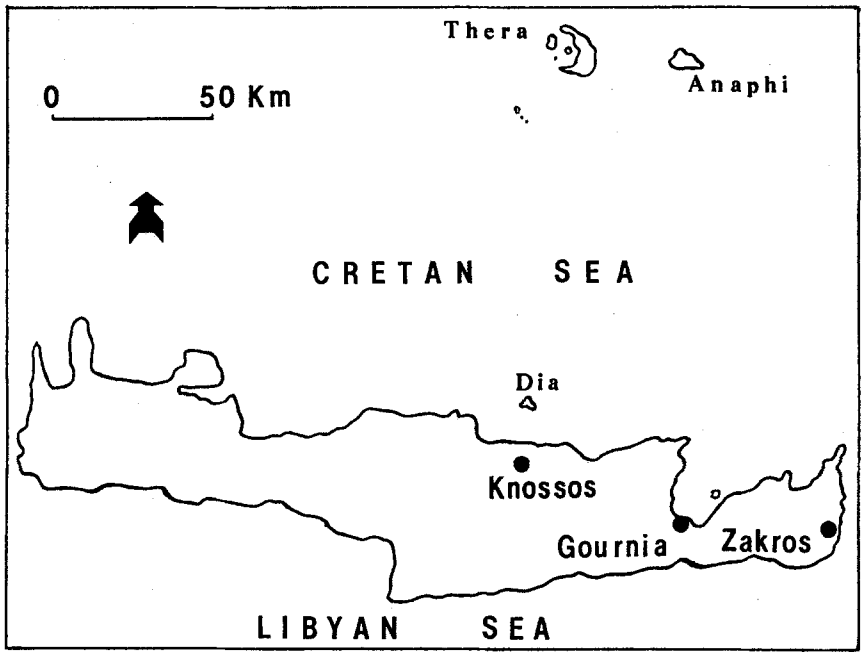


Fig. 2. The island of Crete with Minoan towns in the Bronze Age.

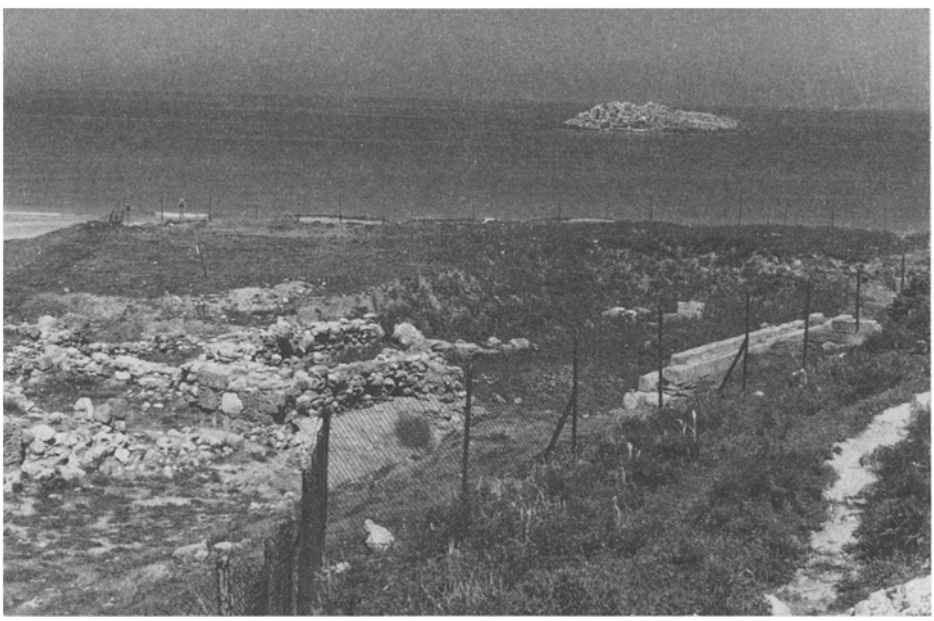


Fig. 3. Ruins of Minoan houses on the coast of Amnissos. The coast is partly protected by the islet of Dia seen in the background.

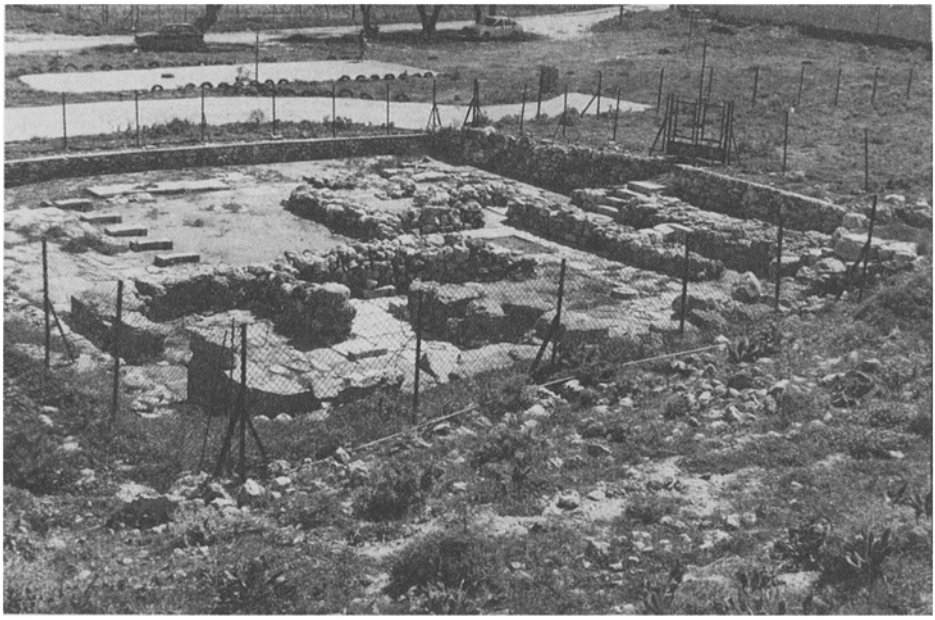


Fig. 4. Ruins of Minoan houses on the coast of Amnissos. This low-lying site would have been extremely vulnerable to attacks by tsunamis.

the downfall of Crete was due, not to foreign invasion but to a natural catastrophe of unparalleled violence and destruction. He suggested that the source and focus of this cataclysm was the volcanic island of Thera.

The first scientific attempt to evaluate the exact date of the eruption was after the earthquake of 9 July 1956 at Thera. This earthquake disturbed the lower strata in the large tephra quarry near Phira, and the ruins of what appeared to be an ancient building were noticed under the bottom layer of pumice. Galanopoulos (1957) arranged for a carbon-14 dating. Two quite different dates were obtained: 1090 plus or minus 150 years, and 1410 plus or minus 100 years. The first date was discounted as the sample was believed to have been contaminated by humic acid. Marinatos (1967) published a more refined carbon-14 dating of similar material. At the Phira quarry, a small tree was found still upright in the lowest pumice layer. This is important evidence because it shows that the tree was still alive when the eruption begun. A sample from the tree was divided into two parts, and each part was counted six times. According to the results, the first fall of pumice occurred between 1603 and 1516 BC.

Another approach as to the dating of the eruption is archaeological. Since written evidence from the Aegean Bronze Age is generally scant, archaeologists relied on an analysis of changing pottery styles in order to establish a chronology of Aegean history. This method, although a subjective art rather than an exact science, has been proven more accurate than carbon-14 dating in cases where the required date is more than several hundred years old. Baker (1963) has pointed

out a number of factors which inevitably introduce uncertainties about radiocarbon dates. These include the 'isotopic fractional effect' in the case of wood samples, which can cause errors of plus or minus 80 years; systematic errors due to the choice of reference material; the effects of the burning of fossil fuels; atom bomb tests; and long-term fluctuations in the level of carbon-14 in the atmosphere over the past 1300 years.

Recent investigations about the exact time of the great eruption seem to agree on a date of about 1670 BC. This date is inconsistent with the archaeological assumption, but is supported by many scientists. Hubberten *et al.* (1989), running radiocarbon tests on samples from Akrotiri concluded that the catastrophic eruption which destroyed the village of Akrotiri occurred in the 17th century BC, most probably between 1700 and 1640 BC. Hammet *et al.* (1987) concluded that the Theran eruption took place in 1645 BC plus or minus 20 years. LaMarche and Hirschboek (1984) by studying frost damage zones in annual tree rings, dated the eruption to between 1628 and 1626 BC. This date was subsequently rejected by Warren (1984) who tried to show that the 1626 BC frost ring did not correspond with the Thera eruption.

The pottery time clock indicated that the first major fall of pumice on Thera occurred at about 1550 BC. However, it is important to remember that this date is the date of the beginning of the eruption and not of the widespread destruction in Crete. It is also the date when the Thera volcano became active again after a long period of quiescence and ejected the coarser pumice which form the lowest layer in the tephra deposits. The effects of this phase of the eruption were probably confined only to Thera. It did not result in the formation of the caldera, but all settlements on the island were obliterated, and all the inhabitants were either killed or driven away. Thus, since just a few skeletons and valuables have been found, it seems as if the inhabitants had enough warning to collect some of their belongings and evacuate.

Finally, Betancourt (1987) discussing the archaeological time-scale, proposed a revised Aegean chronology which fits almost completely into the picture obtained by the recent radiocarbon dates, which indicate between 1700 and 1640 BC as the most probable date for the Thera eruption.

Chen (1989), in an article in the American journal *Discover*, concludes that the great Minoan eruption occurred at 1620 BC plus or minus 20 years. Therefore, it cannot be responsible for the destruction of the Minoan empire. His conclusion is based upon recent scientific investigation and cannot be ignored. But, even if a date around 1600 BC is accepted, this does not mean that the volcanic eruption of Thera left the Minoan empire untouched. There are too many indications supporting the theory that the eruption played the main role in the destruction of the Minoan empire. The existence of pumice from Thera at locations in the eastern Mediterranean (Figure 5), the evidence of destruction from seawaves in northern Crete, and the great destructive power of the Krakatoan-type eruption indicate the cause of the Minoan empire's destruction.

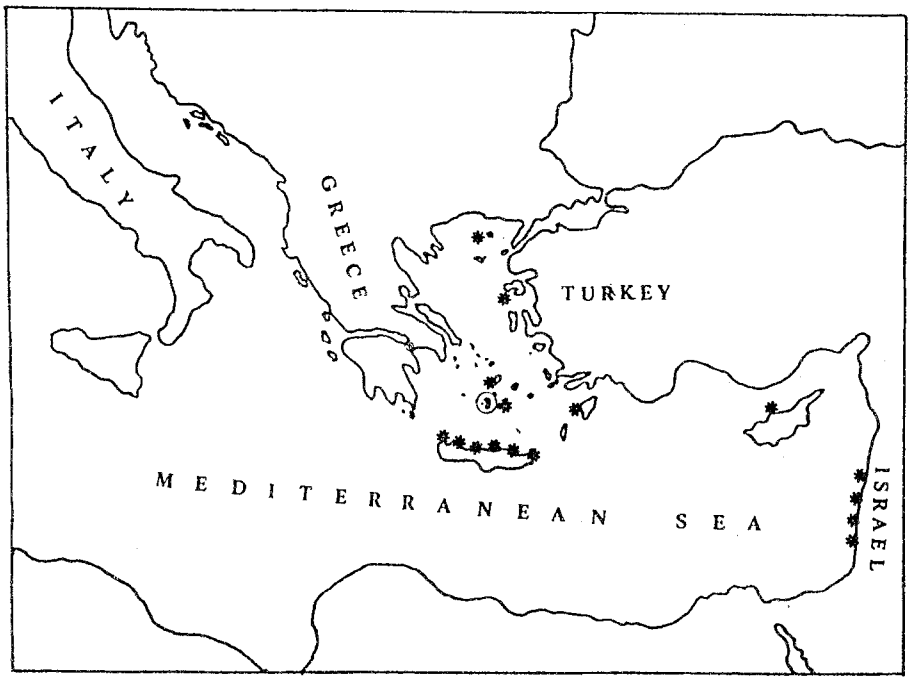


Fig. 5 Locations in the eastern Mediterranean where pumice from Thera has been found.

Even in Greek mythology the statement that ". . . a Bull from the sea was sent by Neptune to plague Minos", suggests the occurrence of a destructive tsunami which swept away the northern coastal towns of Crete. Coincidentally, Neptune was the god of earthquakes.

The appearance of Mycenean-style pottery in the early 16th century BC is not irrelevant to the eruption. The eruption and the ensuing tsunami destroyed most of the Minoan trade ports in the Aegean Sea, the Myceneans grabbed the opportunity to advance their trade activities into the Aegean Islands. It is beyond dispute that the power of the Minoans was derived from their monopoly of the bronze (copper and tin) trade. The Minoan capability of manufacturing arms is well known and continued in full force during the Neopalatial period. McDonald (1984) refers to a Knossian sword manufacturing workshop which exported its products throughout the Aegean and the Dodecanese Islands. But the Minoans were importing most. of their copper and tin supplies from the Near East and Egypt. By losing ground in the copper and tin trade to the Myceneans during the 16th and 15th centuries BC, they lost most of their trade power. And this happened because of the destruction of their trade ports and ships in the Aegean from the Thera eruption and the tsunami generated by it.

Thera lay right in the center of the network of Minoan bases in the Aegean. It

is the nearest Cycladic island to Crete. According to Marinatos (1968), the first outbreak of Thera's volcano obliterated a rich settlement on Thera itself. The culminating paroxysm, with its seismic waves and fall-out of ash, was like a dagger plunged into the heart of Crete. The waves destroyed Minoan naval power, halted trade activities, and the ash disrupted the island's agricultural economy. Minoan Crete was battered to her knees by the brute forces of nature, and never rose again.

3. The Volcanic Eruption at Thera and Seismic Seawaves (Tsunamis)

Although many scientists are disputing the actual date of the volcanic eruption at Thera, none of them disagrees with the fact that a paroxysmal eruption of extreme violence occurred on Thera during the Late Bronze Age. But, was the eruption responsible for destructive tsunamis, too? Indeed, scientists who argue that the eruption was accompanied by tsunamis have the support of many archaeological as well as scientific discoveries, which cannot be ignored.

Marinatos (1939) in his article published in *Antiquity* was the first to claim that the eruption was followed by a great tsunami which literally swept away the Minoan empire, except for the palace of Knossos. His thesis though, did not supply adequate scientific evidence. Thus, his argument remained to be proven by findings from excavations at Thera and at other islands in the Aegean Sea. Marinatos (1934) started investigational excavations on Thera and Crete as early as 1932. In a building adjacent to the sea, at Amnisos in Crete, he discovered that the lower levels were deeply buried by masses of pumice, stone, and sand. For him it was clear that the building had been swept away by a tsunami, and that later sea-borne pumice was washed over it by normal wave action, and deposited in the cavities of the ruins.

During November 1961, Marinos and Melidonis (1961) made some significant discoveries during an excavating expedition to the island of Anaphi, 24 km east of Thera (Figure 6). At four locations, they found layers of white pumice from Thera. Three of these locations were at an altitude of 30 to 40 m while the fourth was at a height of 250 m above sea level. Of course, the height of the tsunami would have been far less than 250 m but this location lies at the end of a funnel-like valley where the height of the waves could have increased and the water could have climbed to this elevation, depositing the floating pumice when it receded.

In 1967; Marinatos visited the Villa of the Frescoes in Crete, located a little higher inland from Amnisos. He noticed that the walls and corners of the rooms of the Villa had collapsed in an unusual way. The outward bulge of the walls, and the fact that huge orthostats of up to 2 m long by 1 m broad were prised out of position or were missing altogether, made him conclude that they were caused by the sucking action of a huge mass of receding water. Antonopoulos (1979) estimated that the water mass struck the orthostats with a speed of at least 2.5 m/s. Also in the Villa there was evidence of extensive fire damage, a point which seems

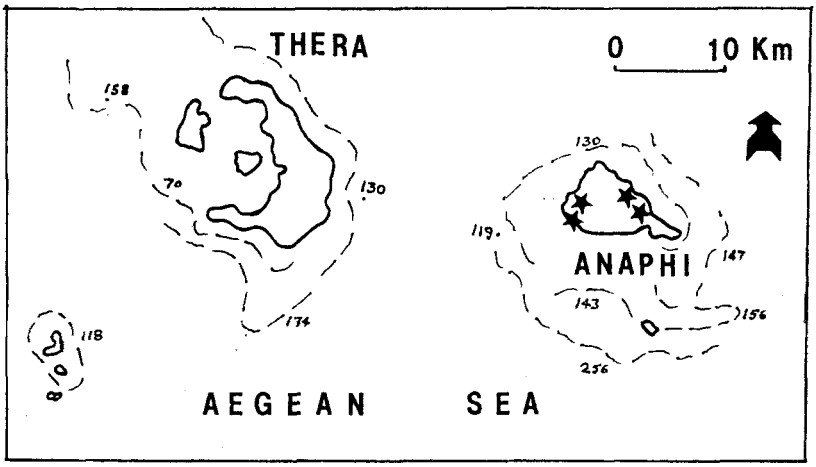


Fig. 6. The island of Anaphi. The stars indicate the places where pumice from Thera has been found.

to be inconsistent with the tsunami theory. Marinatos argued that the fire could have been caused by the overturning of lamps, as a result of the accompanying earthquake, or that the villagers burned fixtures, which spread the fire around, to counteract the pall of darkness from the eruption. However, one could object that such reasoning is mere guess-work and is not evidenced.

Since the great Minoan eruption of Thera volcano in the Late Bronze Age, the Aegean has witnessed many natural catastrophes from earthquakes which generated tsunamis. From investigations of these natural hazards, indirect evidence is supplied for evaluation and correlation with the Minoan eruption. Galanopoulos (1960), Ambraseys (1962), Antonopoulos (1979), and Soloviev (1990) have published catalogs of the tsunamis in the eastern Mediterranean, including detailed descriptions of every event.

On 21 July 365 AD, Knossos, Gortyn, and eight other places in Crete were destroyed by an earthquake, and associated destructive tsunamis were reported from Sicily, the Adriatic coasts, Epirous, Methone, Epidaurus, Crete, the Boeotian coasts, and from as far as Alexandria where ships were carried over buildings and left in the streets of the city.

In 1672 Thera was shaken by an earthquake. The island of Kos was reported to have been 'swallowed up', presumably by a tsunami generated by the earthquake.

On 29 September 1650, there was a destructive earthquake on Thera followed by a submarine explosion from the Kolumbo volcano whose crater lies in the sea off the north-east flank of the island. There was also a devastating tsunami preceded by a large withdrawal of the sea, particularly on the east coast. On the island of Tos, waves of up to 16 m high were reported. In Crete rowing boats were sunk in Herakleion Harbor.

On 9 July 1956, a well documented earthquake occurred which was centered near the south-east coast. of Amorgos Island. Professor Ambraseys (1962) reports:

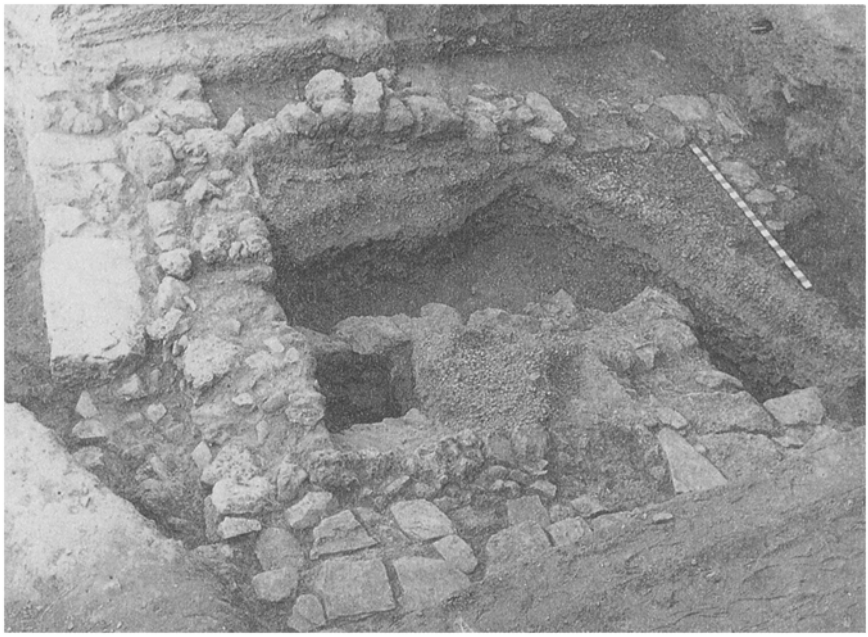


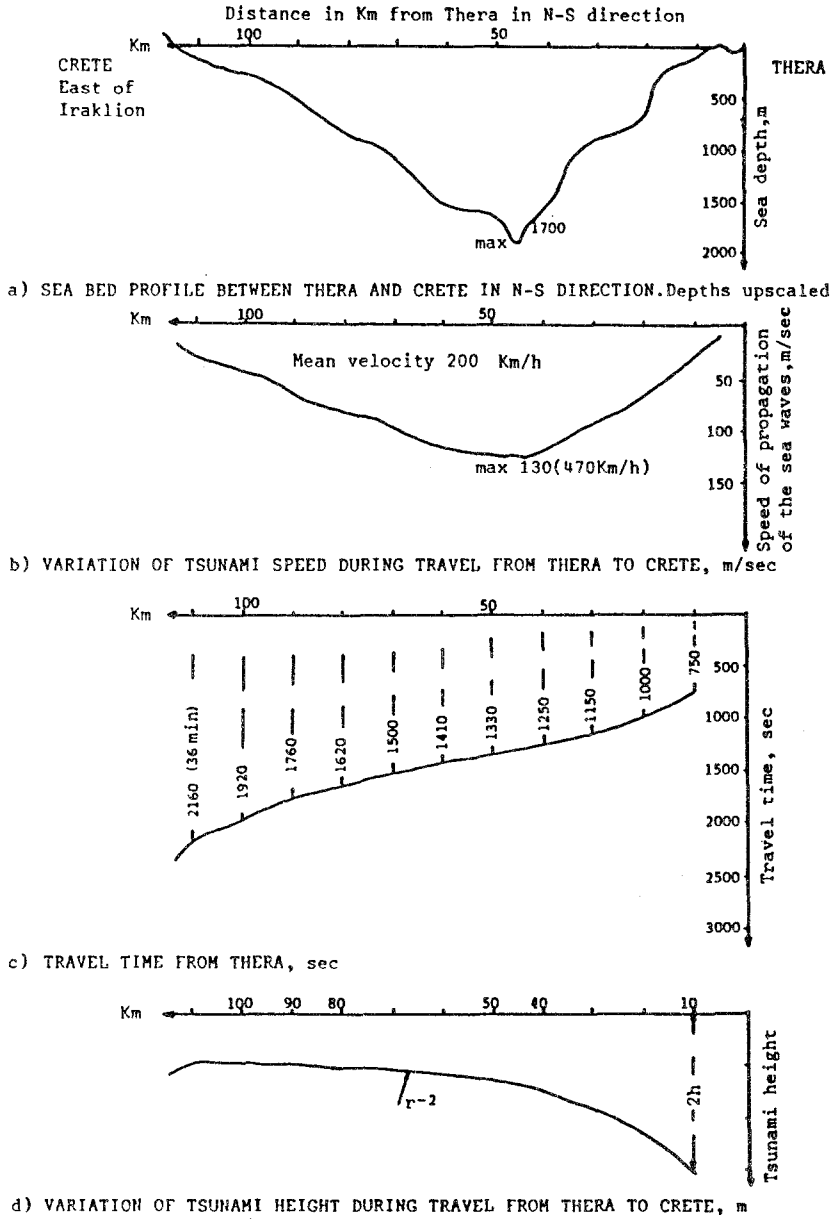
Fig. 7. Pumice deposited on the floor of a levelled room in the village Kastelli near Chania. Photo by J. Tzedakis.

"the earthquake (magnitude 7.8) was followed by a severe seismic-wave most probably produced by a series of landslides on the steep banks of the submarine trench of Amorgos. Amorgos itself, Ios, Astypalaea, Kalymnos, Leros, Nisyros, Kos, and Karpathos suffered severe damage. Minor damage was reported from Patmos, Crete, Tinos, Melos, and Seriphos. The height of the wave varied: on the coasts of Amorgos and Astypalaea facing the epicenter they were from 25 to 40 m high; on the opposite coasts of the same islands, only 2 to 4 m high".

Francaviglia (1989) reports that after XRF analysis on pumice samples found at various locations in the Aegean sea (Figure 5), pumice from Samothraki, Amnisos, Kastelli (Figure 7), and other locations, proved to have originated from Thera. The pumice found at such distant places as Samothraki, which lies in the northern Aegean, seems to have been carried by the tsunami and then drifted in the Aegean for a long time. This is in good agreement with Callimachos, who tells us that before Apollo came to Delos the island was called Asterie 'star island' and that it floated round the Aegean, and was seen in various places.

As destructive seismic sea waves have been associated with the above-mentioned seismic activity centered in or near Thera, and as they were certainly associated with the Thera eruption which is analogous to that of Krakatoa, it seems reasonable to conclude that they accompanied the great Bronze Age eruption, especially in its final caldera-forming stage (Pararas-Carayannis, 1973).

The destructive effect of tsunamis depend on their height, speed, and the



Fig, 8. Estimated data concerning the tsunami generated by the volcano eruption at Thera during the Bronze Age.

configuration of the surrounding coasts. The deeper the sea, the swifter the wave. Around Krakatoa, the waters are quite shallow (50 to 150 m). Nevertheless, speeds of up to 41 m/s were calculated for the tsunamis associated with this eruption. Between Thera and Crete, the average depth of the sea is 1000 m (Figure 8a). The map of the area shows that the northern coasts of Crete (Figure 2) are exposed

Fig. 9. Ruins of Gournia on the northeastern coasts of Crete.

to waves coming from Thera. Thus, large tsunamis could have spread devastation over all the coastal plains and offshore islands, and at the heads of bays like the Gulf of Mirabello and Siteia Bay. The great palace of Mallia lay only about 600 m from the coast, just a little above sea-level. Harbor towns like Amnissos, Katsamba, Nirou Khani, and Gournia (Figures 9 and 10) could have been totally destroyed just as Tyringen and Anjer on the Java coast. On the east coast, Itanos, Palaiokastro, and Kato Zakros (Figures 11 and 12) where its newly discovered palace is only about 100 m from the present shore, could have been inundated by the tsunami. Only Knossos, the greatest Minoan palace, would have had a chance of escaping annihilation. It lies at a distance of 5 to 6 km inland and is sheltered from the sea by a low range of hills. Also, the island of Dia (Figure 3) lies like a protecting screen off the coast directly between it and Thera.

In order to get a rough idea of the destructive power of the tsunami which followed the collapse of the central part of Strongili, a calculation of its height would be adequate. The amplitude of a tsunami is proportional to the initial amplitude and inversely proportional to the square root of the distance the wave has travelled. Professor Pfannenstiel (1960) found layers of sea-borne pumice in sediments of a postal-glacial terrace 7 m above sea-level, north of Jaffa (Tel Aviv) (Figure 5). According to Pfannenstiel, these layers come from the eruption at Thera. Taking into the account the discovery of Pfannenstiel, Galanopoulos and Bacon (1969) estimated that the sea waves, produced by the collapse of Strongili must have had a height of about 50 m at their starting point (Thera) in order to

Fig. 10. Ruins of Gournia. It is the only completely excavated town of the Bronze Age in the Aegean.

Fig. 11. Ruins of the Palace of Kato Zakros in eastern Crete.

Fig. 12. Ruins of the Palace of Kato Zakros in eastern Crete.

travel the distance between Thera and Jaffa (900 km) and still maintain a height of about 7 m.

During the bronze Age, around 1550 BC, a dominant maritime power, the Minoan empire, declined because of a frightful cataclysm. At almost the same time, a round island in the Aegean, Strongili, collapsed into the sea in a large volcanic eruption with side effects which caused such devastation to Minoan Crete that the Minoan empire never recovered. All the evidence, historical, geological, and archaeological suggest this. It remains for future researchers to discover more evidence to persuade those who are still skeptical about the connection of the Bronze Age eruption at Thera and the destruction of the Minoan empire in Crete.

4. The Tsunami Generated from the Great Thera Eruption

There is no doubt that the seismic activity which was centered on Thera during the Bronze Age was all that was needed for the generation of a great tsunami. Associating the eruption at Thera with the analogous Krakatoa eruption, it seems reasonable to assume that tsunamis accompanied the great Bronze Age eruption, especially in its final caldera-forming stage.

Marinos and Melidonis (1961) found evidence of the tsunami in Anaphi at elevation of between 30 and 40 m. This is in good agreement with an estimation of about 42 m by Pararas-Carayannis (1988) for the tsunami at Anaphi. The estimate was obtained on the basis of the tsunami height attenuation at Jaffa-Tel

Aviv assuming an entirely geometrical dispersion and not the effects of refraction, diffraction, or resonance.

The highest possible tsunami wave at Thera could not have exceeded 50 m. Pararas-Carayannis (1974) states that a tsunami height of more than 50 m cannot. be supported by a tsunami source mechanism that involves only the explosion collapse of the Santorini volcano, no matter how fast this happened.

Antonopoulos (1979, 1983) assuming a probable height for the tsunami of 30 m at Thera estimated that the tsunami height in the northern coasts of Crete should have been about 12 m. This is about 40% of the tsunami height at Anaphi, but still adequate enough to have destroyed the northern and eastern coast towns of Minoan Crete. In Figure 8, the diagrams show the estimated data of the speed of propagation and of the height of the tsunami in association with the distance travelled and the sea depth. From these estimates, Antonopoulos concluded that the tsunami struck the coast, where the city of Herakleion is now, in 36 min with a speed of 470 km/h.

Papazachos (1989), after consideration of the largest eruptions of the Santorini volcano during the last five centuries, which occurred in 1457, 1573, 1560, 1866, and 1925 and were accompanied by tsunamis, estimated that the probability of the occurrence of a strong volcanic eruption at Santorini accompanied by tsunami is about 0.1 for the next 50 years and 0.95 for the next 110 years.

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