The Minoan Eruption of Santorini around 1613 B.C. and its consequences

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Zusammenfassung

Die Minoische Eruption des Santorini Vulkans in der Spätbronzezeit im ägäischen Raum ist wahrscheinlich eine der stärksten, die die Menschheit je erlebt hat. Vor dem Ausbruch hatte Santorini eine ähnliche Form wie heute: Eine Ringinsel mit einer wassergefüllten Caldera, in deren Zentrum sich eine Insel befand. Die Öffnung der Caldera lag im Südwesten. Allerdings änderte der Vulkanausbruch nicht nur die Form dieser Ringinsel, sondern begrub sie zusammen mit blühenden Siedlungen unter einer dicken Bims- und Ascheschicht. Alles Leben auf Santorini wurde zerstört. Die bei der Eruption ausgestoßene Vulkanasche ging über dem östlichen Mittelmeergebiet nieder, heute bildet diese Ascheschicht einen wichtigen archäologischen Leithorizont. Der Fund von zwei Olivenbäumen in den Jahren 2003 und 2007, die vom Bimsstein der Minoischen Eruption begraben wurden, ermöglichen es, absolute und präzise Radiokohlenstoffdaten zu bestimmen: 1613 ± 13 v.Chr. kalibriert. Neben der Zerstörung von Santorini selbst wurde die ganze Region von Erdbeben, Tsunamis, fließendem Bimsstein und Ascheregen heimgesucht. Dass Tsunamis die Küstenregionen der umliegenden Inseln verwüstet haben müssen, ließ sich jüngst an der Nordküste Kretas belegen. Währenddessen löste die Aschewolke möglicherweise globale Klimaveränderungen aus, die eine Zerstörung der Ernten im östlichen Mittelmeergebiet zur Folge hatten. Dies, zusammen mit der Zerstörung der Flotte durch Flutwellen, muss ernste Konsequenzen für die Minoer gehabt haben

Summary

The Minoan Eruption of Santorini in the Late Bronze Age was one of the strongest experienced by humankind. Before the eruption, the shape of Santorini was similar to the one it has today: There was a ring-island: a water-filled caldera with an island in the centre. The caldera had an opening to the southwest. The eruption not only changed the shape of that ring-island but also buried flourishing settlements under a thick layer of pumice and ashes. All life on Santorini was destroyed. The Minoan Eruption left a synchronous layer of tephra over the eastern Mediterranean region which is an important marker of chronology. For example, when two olive trees, buried alive in the pumice of the Minoan Eruption, were found in 2003 and 2007, it was possible to determine a precise radiocarbon date: 1613 ± 13 cal. B.C.

Besides the destruction on Santorini itself the entire region was hit by earthquakes, tsunamis, floating pumice, and ash fall. Tsunamis must have devastated the coastal areas of adjacent islands, as recently evidenced on the north coast of Crete. Meanwhile, the eruption cloud might have triggered global climatic changes that resulted in the destruction of harvests in the Eastern Mediterranean. These, together with the destruction of the Minoan fleet by tsunamis, must have had severe effects on the trade network in the area – for a few generations at least.

Introduction

This fan of tephra of the Minoan Eruption provides a valuable time marker for geologists and archaeologists because all objects that are in direct and undisturbed contact with the tephra are synchronous. Thus, dating this tephra layer is of paramount interest for the chronology of the Aegean world, Egypt and the Levant as well. Furthermore, the thick ash deposits left by the Minoan Eruption have led to much discussion and speculation. Even today, after thorough investigations of the up to 60-metre thick pumice layer, there is still controversy over the puzzling observations related to its history (Fig. 1). Likewise, the observation of large pyroclastic flows on the sea bottom around Santorini in 2006 led to a revival of the discussion of the size of the eruption. Moreover, the discovery of damage on the north cost of Crete and islands off the west coast of Anatolia (see Bertemes in the present volume) by tsunamis triggered by the Minoan Eruption have changed our views considerably. Today some scholars see the eruption of Santorini and its catastrophic consequences as a possible cause of cultural changes in many places in Europe around 1600 B.C.

In historic time, only the volcanoes Tambora (1815) and Krakatau (1883) had eruptions of similar magnitude. In the catalogue of known volcanic eruptions (Simkin et al. 1981), the strengths of explosive eruptions have been classified according to a volcanic explosivity index (VEl) based on quantitative criteria. In this index, the Minoan Eruption was a ›heavy-weight‹ with a value of 6, just below that of the Indonesian volcano Tambora (VEl=7) and equivalent to the eruption of Krakatau. However, investigations by H. Sigurdsson et al. (2006) indicate that the eruption was stronger than previously assumed. A VEI value of 7,1 is currently discussed, which, if accepted, would mean that it was bigger than the Tambora eruption in 1815 and about ten times as big as the Krakatau eruption in 1883.

Equally remarkable are the products of the eruption, especially the pumice. Because it is formed of a light, porous volcanic glass, it floated for months on the water and could easily be carried for great distances by wind and waves. Its distribution has played an important role in reconstructing the mechanism of the Minoan Eruption. While the wind carried pumice to the east, the sea currents carried pumice in a south-easterly direction. Eventually, the eruptive material that reached the stratosphere was carried to the north, which will be shown later.

When did the eruption happen?

Over the past 40 years, there have been prolonged discussions about when the eruption occurred and major discrepancies have arisen in the results of scientists and archaeologists. While some archaeologists used evidence from pottery and the styles of design elements to date the eruption to around 1500–1520, a series of radiocarbon dates, ice-core dating and dendrochronological observations pointed to ages of about 100 to 150 years earlier.

Absolute and relative dating methods

Frost damage to trees of North America may be traceable to the Santorini eruption. Frost damage related to volcanic eruptions has been observed, not only in America (LaMarche/Hirschboek 1984) but in Europe as well. M. Baillie and M. A. R. Munroe (1988) provided a firmly established age for frost damage in the annual rings of oaks found in a bog in Ireland.

However, this method has the serious disadvantage that climatic variations responsible for the frost damage can also be caused by other natural events, such as the shifting of ocean currents, known as El Niño, observed off the coast of Chile.

Dendrochronology for dating the Minoan Eruption have so far failed, because wood tends to be poorly preserved and suitable material has yet to be found at Akrotiri.

Ice core dating has also made very important contributions for dating the Minoan Eruption. The presence of an acid signal in the Greenland ice showed that the eruption obviously was strong enough for the eruption column to reach the stratosphere where the ejecta were carried over a large part of the northern hemisphere (Hammer et al. 1987).

At present, three continuous ice core drillings exist, all of which reached the bottom of the Greenland ice sheet and contain the Santorini acid signal (DYE 3, GRIP and NGRIP). Not included are the drill cores from Camp Century and GISP 2 in this list, because the first mentioned was withdrawn by the authors, and the second lost a part of the ice core exactly in the range where the Santorini acid signal was expected (Hammer et al. 2003). A comparison of the three usable cores shows that the Santorini acid signal diminishes in strength from south to north, which might indicate that the eruption cloud spread in that direction from a source south of Greenland. While examining the acid signal from Santorini in the GRIP- and NGRIP drillings, tiny fragments of ash shards were found and analyzed by means of various mineralogical and chemical methods. It appeared that there was a striking similarity with the pumice from Santorini.

Further research improved the precision of the result from 1645 ± 7 B.C. to 1645 ± 4 B.C. (Hammer et al. 2003). In 2006 B. M. Vinther et al. re-examined the ice core data and placed the signal in the year 1642 ± 5 B.C. Back in 1996, the archeologist Lord C. Renfrew had commented in an article in the journal Nature: »One grain of Theran tephra at the appropriate point in a single Greenland ice core would be enough to establish a sound link going beyond mere supposition«. However, when C. U. Hammer et al. (2003) published their ash findings from the Greenland ice core, some scientists rejected a linkage of the ash shards to the Santorini eruption. They claimed that the signal originated from Aniakchak, at a more northerly latitude (Eastwood et al. 2004). Furthermore, D. J. Keenan (2003) had objections that were based on the statistical methods used by C. U. Hammer et al. He argued that their results did not clearly point to Santorini as the place of origin. Also J. S. Denton and N. J. G. Pearce (2008) postulate: »The geochemical evidence is however so compelling that no reasonable doubt can remain that the 1642 B.C. ice core ash is from Aniakchak…«. However, B. M. Vinther et al. (2008) reject this postulate. The intensity of the acid signal – as mentioned before – observed on several drill sites shows that it originated from a volcano south of Greenland.

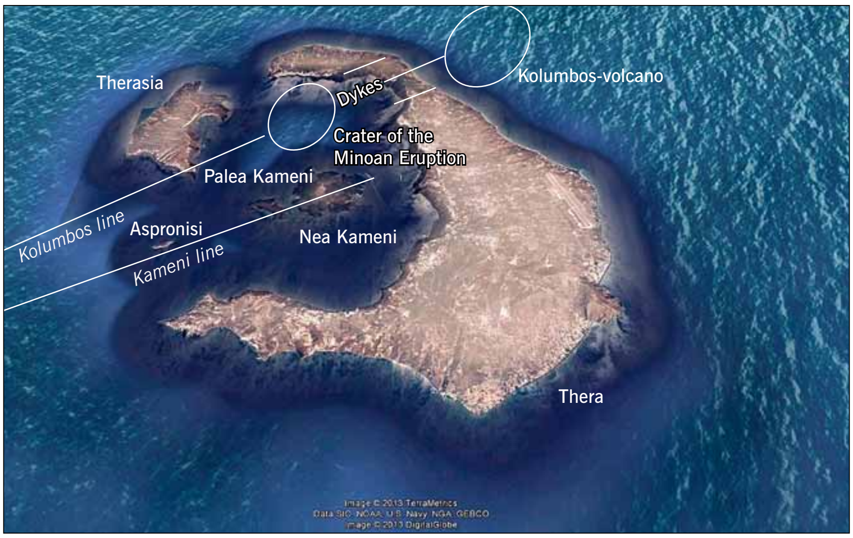

Fig. 1 Satellite image showing Santorini and the surrounding sea bottom. Due to gravity the morphology of the sea bottom is visible on the surface of the sea where it can be seen when photographed at a oblique angle. Thus tectonic lines and submerged volcanoes become visible. The crater of the Minoan Eruption is clearly visible as a white area (ca. 400 m deep) in the caldera between Thera and Therasia (**marked with a circle**).

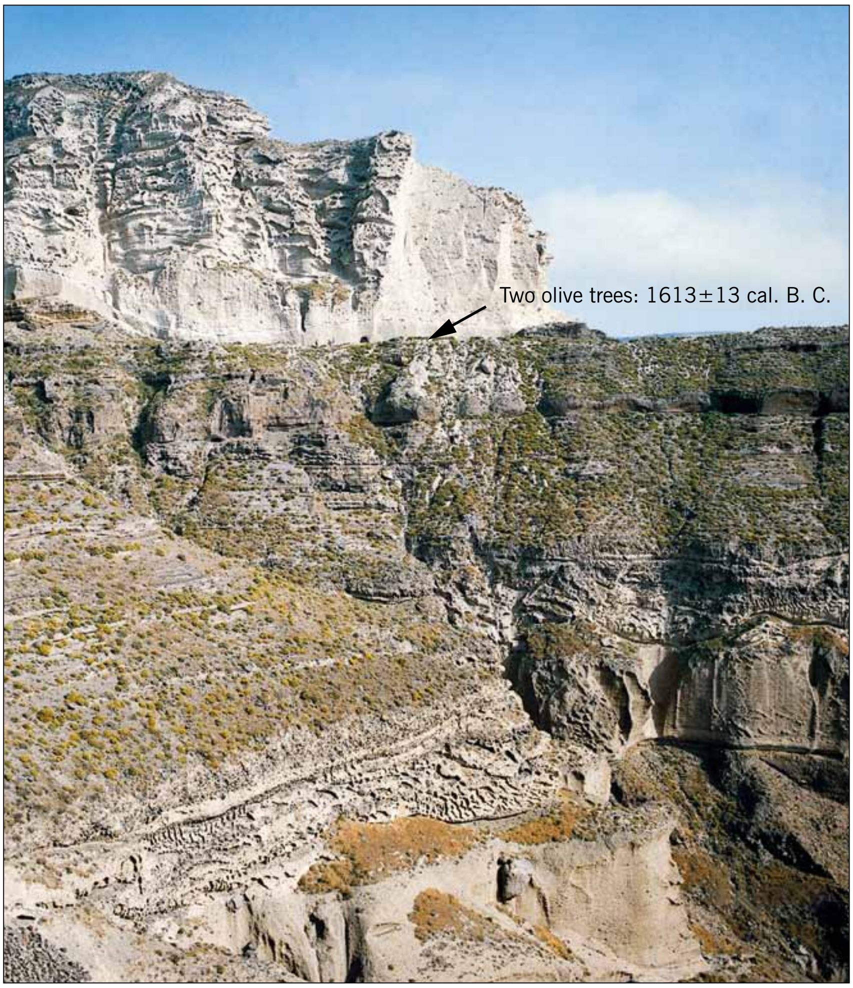

Fig. 2 The picture shows the caldera wall north of Athinios on Thera where in a height of 150 m above sea level two olive trees were found under a ca. 40 m thick layer of pumice produced by the Minoan Eruption.

Radiocarbon dating. The unique discovery of an olive tree by T. Pfeiffer (2003) that had been buried alive in the pumice from Santorini opened quite new perspectives (Fig. 2). The tree was still standing when it was buried. If the last tree ring was preserved there would be a good chance to date the Minoan Eruption quite exactly. A detailed description of this find and its investigation is published elsewhere[1].

The new date for the eruption of 1627–1600 cal. B.C. gave rise to heated discussions. While some scholars agreed with the new date (Manning et al. 2006), others rejected it, arguing that the branch might have been dead. In 2007 a new olive tree with a 183 cm long stem was excavated (Friedrich/Heinemeier 2009; Friedrich/Sigalas 2009) only 9 m from the first tree. It was buried alive just like the first tree (Fig. 3–4). In order to settle the arguments of some scholars that the first branch might have been dead when buried, we decided to go through the dating process again. This second tree and a new series of samples taken from the first olive branch are currently being investigated by four radiocarbon laboratories in order to confirm or reject the previously measured date. Preliminary results of the new dating, however, show that the new result is close to the one published in 2006. This means that the eruption occurred in the seventeenth century and not in the sixteenth century B.C. The phases of the Minoan Eruption and their distribution on Santorini are described in detail elsewhere[2]. For this reason, only a short overview is given here.

Warning before the disaster

Clear indications of premonitory activity have been found in the excavations at Akrotiri: Broken steps, collapsed walls, houses reduced to ruins, and heaps of debris gathered by the inhabitants have been found beneath the earliest deposits of the Minoan Eruption (Fig. 5). The inhabitants were certainly aware of the impending eruption, for they had time to remove food and valuables from the ruins. In one place, for example, they removed a set of three beds from the ruins and had placed them one atop the other with their posts upright (Fig. 6).

Fine dust from the volcano was deposited in the Akrotiri settlement (Doumas 1974). G. Heiken and F. McCoy (1984) showed that this fine dust-layer, which is only visible on the Akrotiri Peninsula, is the result of phreatomagmatic explosions during the opening phase of the Minoan Eruption. These explosions were an additional warning that forced the inhabitants to flee.

1 Friedrich et al. 2006; Friedrich 2009; Heinemeier et al. 2009.

2 E.g. Pichler/Kussmaul 1980; Druitt et al. 1999; Friedrich 2009.

Fig. 3 The photo shows the site where two olive trees were found buried alive in the pumice of the Minoan Eruption. On the left corner a man-made wall from Bronze Age is visible.

Pumice fall – the first phase of the eruption

The first layer deposited was light grey pumice. It has a maximum thickness of five metres in the region of Fira on Thera and thins rapidly toward the north, south, and west. At Cape Akrotiri, it is only 80 cm thick; on Therasia to the west, it is 30 cm thick, and at Oia in the north, only 50 cm (Fig. 7). From these thicknesses, it has been determined that the main wind direction during this phase of the eruption was toward the east. Calculations by D. M. Pyle (1990) show, that the eruption column, from which it fell, reached a height of 36 km to 38 km. This is in agreement with previous calculations by L. Wilson (1980) to the effect that the eruption column of the Plinian phase reached the stratosphere, and dust and gases as well as aerosols were spread through the stratosphere of the entire northern hemisphere. This material was carried at least as far as Greenland[3].

The first explosive phase was very strong. As the reconstruction from the deposits shows, it began in a part of the ring-island where rising magma did not come into contact with seawater. The location of this eruptive vent is well established from various observations, such as the thickness and grain size of the eruptive products. It is also visible as the deepest hole in the caldera on a satellite photo (cf. Fig. 1).

One can further conclude that in the first phase, material containing pumice was ejected to a great height and that most of it fell back on the volcano and the surrounding sea. Sea currents carried the floating pumice over a wide region, while the wind carried fine ash eastward as far as Anatolia and the Black Sea (Sullivan 1988).

Base surge – the second phase

On Santorini the deposits of the second phase are easily distinguished from those of other phases due to their large undulating layers, some of which have wavelengths of up to ten metres. Owing to the fine grain size of the pumice, it can easily be recognized even from a great distance.

Volcanologists are now in agreement about the origin of this unit: In the second phase of the eruption, the eruptive mechanism changed completely. The feeding vent of the Pre-Kameni Island had evidently widened, so that its surroundings broke down and cracks allowed seawater to enter. The coming together of seawater and fluid magma led to

3 Hammer et al. 1987; Hammer et al. 2003; Vinther et al. 2008.

Fig. 4 A second olive tree was excavated in 2007. The photo shows the site where it was found standing *in situ* in the pumice of the Minoan Eruption.

especially violent phreatomagmatic reactions. The magma was torn into small particles, which were surrounded by a thin layer of expanding steam. Clouds of ash suspended in steam spread outward from the eruption centre in expanding rings and filled the entire caldera. They ascended the caldera walls, swept over the lower parts of the rim, and flowed down the outer slopes of the volcano (Fig. 8).

On Thera, one sees that these so-called base surge deposits have a very distinctive distribution. At Mount Profitis Elias, for example, they are found only at elevations below about 350 m. A similar situation is also seen on the flanks of Megalo Vouno Volcano. One can conclude, therefore, that during this phase the horizontally directed cloud flowed outward from an eruption centre and over low parts of the caldera rim, sparing only the highest peaks.

In both the first and second eruptive phases, huge pieces of lava were torn sporadically from the walls of the feeding vent and thrown out as blocks. They are clearly visible in the ash layers forming ›bomb sags‹. Blocks more than a metre in diameter reached the Bronze Age dwellings at Akrotiri about eight kilometres from the vent. Even at this distance, they were able to shatter stonewalls.

Pyroclastic flows – the third phase

The tephra of the third phase is easily recognizable in the caldera wall, even from great distances. It can be distinguished from the other layers mainly by the large numbers of dark fragments it contains. The fragments were rounded in the eruption column and mixed with the pumice. Most of these well-rounded, dark, glassy blocks are very similar to the lavas of Skaros Volcano. For the most part, these blocks come from lavas of the Pre-Kameni Island, which were de-

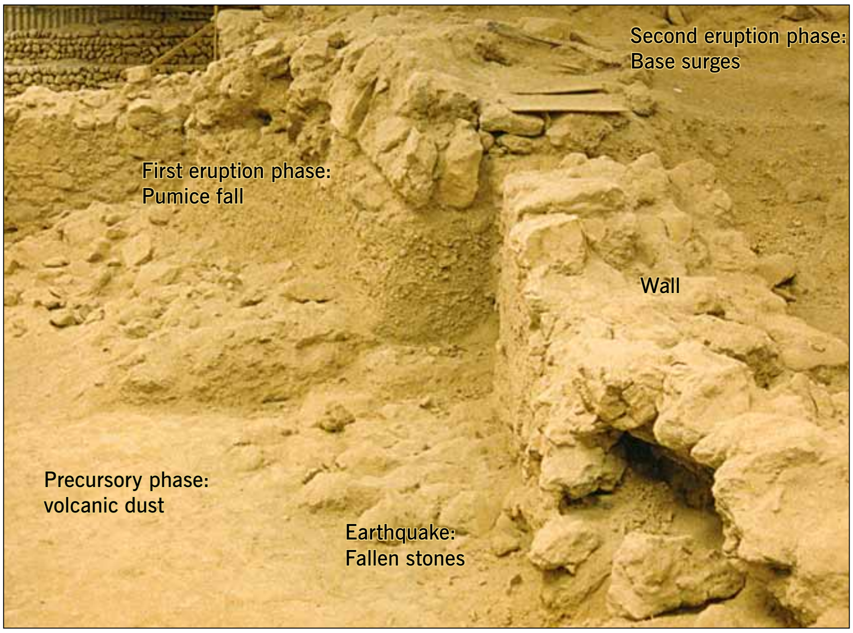

Fig. 5 A photograph of a wall during the Akrotiri excavation shows the effects of the Minoan Eruption: The debris on the ground bears witness to earthquakes prior to the eruption. The white dust on the floor belongs to the precursory phase and the air-fall pumice to the first phase. In the second phase all objects protruding from the surface of the previous phase are chopped off and laid on top of the latter deposits.

Fig. 6 The inhabitants tried to remove some valuables from their destroyed houses, as in this set of three beds which they had placed on top of each other, one with its posts upright. However, earthquakes or other warnings of the impending eruption forced them to leave it behind. The original wood of the beds has long gone, but it left cavities in the pumice that one can fill with plaster and make castings of their form. On the underside of one of the beds the archaeologists discovered a net that was used to wrap the beds.

stroyed during the widening of the vent. As the vent grew wider, more of the crater wall gave way. It has also been deduced that in this phase the ash column did not reach the great heights attained in the first phase. Instead, turbulent clouds of ash and hot gas were directed laterally outward at low angles.

In the deposits of this phase, one finds a variety of types of xenoliths, including light-coloured blocks of stromatolites, which enabled us to show that the water-filled caldera existed already before the Minoan Eruption (Friedrich et al. 1988; Eriksen et al. 1990). The large number of fragments of non-volcanic rock in the third phase of the eruption indicates that the rapid evacuation of the magma chamber led to a collapse of large parts of the low levels of the volcanic edifice. It produced the large northern basin of the present caldera and deepened the earlier-formed southern basins. The latter were partly refilled with pyroclastic material during later eruptions.

Was there a fourth eruption phase?

The profiles in the quarries south of Fira and at Athinios and Akrotiri clearly reveal volcanic deposits that are especially rich in fragments of lava and overlie the pyroclastic flows of the third phase. Their dark colour makes them easy to recognize. Experts disagree, however, as to whether they are primary products of an eruption or reworked material. H. Pichler and S. Kussmaul (1980) mapped them as reworked deposits, G. Heiken and F. McCoy (1984) considered them lag deposits left by the eruption column in the closing phase of the eruption.

The effects of the Minoan Eruption

The Minoan ash layer, which was up to 60 m thick, blanketed the former island ring (cf. Fig. 2). This pumice layer is not present everywhere on the islands; topography has had a great influence on its present distribution. Very little was deposited at the higher elevations, and where slopes were very steep it was removed by erosion. Tsunamis could have washed away some of the pumice at low elevations near the shores.

The original form of the island was also altered by the eruption. It seems that much of what was lost from the central part of the ring-island was added to the outer margins. In particular, the eastern side of Thera was considerably widened by debris washed from the rim and deposited on the alluvial plain. The former island of Monolithos was joined to Thera, whereas the Pre-Kameni Island inside the caldera disappeared completely.

Effects on flora and fauna

These eruptions must have had a profound effect on the vegetation of the older island. Minoan ash deposits destroyed almost everything. The only places where plants were able to survive were at high elevations, such as Profitis Elias and the ridge Platinamos, and on steep slopes in the wind shadow of the eruption.

The same was true for animal life, which had retreated to the upper elevations of the Elias massif. A few small creatures, such as snails, lizards, snakes and insects, survived the catastrophe in such places, while all other land animals perished. Up to now, there are no signs of human losses in the Akrotiri excavation.

Devastations in the vicinity

Pumice and ash must certainly have covered the nearby islands as well. The strong eruption with its ash fall and noxious gases probably had a catastrophic effect on the entire surroundings of Santorini. The islands of Anaphi and Rhodes to the east of Santorini must have been subjected to a rain of ash, which was carried mainly in that direction (Fig. 9). The Minoan ash layer can be recognized in many places on Rhodes (Keller 1980; Doumas/Papazoglou 1980). Ultimately, it reaches as far as Anatolia and the Black Sea. The huge mass of pumice undoubtedly covered the surface of the sea over a wide region and was washed up at higher levels on the shores by the tsunamis, which were triggered by earthquakes and the collapse of the caldera. The causal relation of tsunamis was demonstrated by the earthquake of 9 July 1956, when the tides on the island of Ios reached a height of 25 m. On most of the shores of the surrounding part of the Aegean Sea, lumps of pumice have been found that clearly had drifted there on the surface of the water. Pumice was also found on the northern coast of Crete and on the shores of Anaphe, Limnos, Paros, Samothrace, Cyprus, and even Israel (Francaviglia 1990). It was also observed in the Nile Delta (Stanley/Sheng 1986), and lumps of some centimetres in diameter were found in Bronze Age contexts e.g. at Avaris (Bietak 2005) and Tell al Ajul in the Gaza Strip in Palestine (Fischer 2009). During the transition from the first to the second phase, the eruption column that was directed to the east suddenly collapsed and generated strong tsunamis when the enormous mass of material suddenly entered

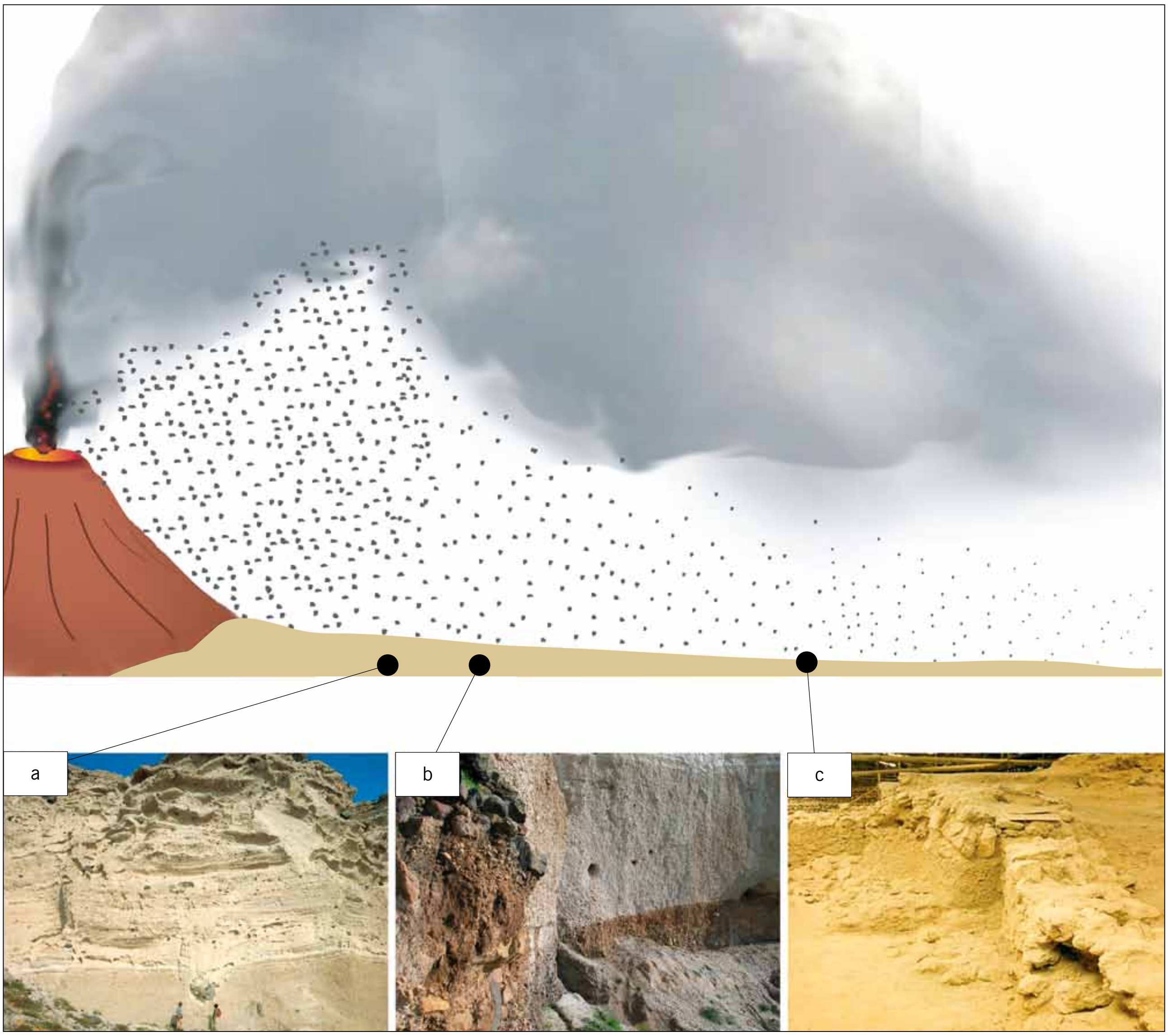

Fig. 7 At a distance from the crater both the grain size and the thickness of the layer deposited by the volcano diminishes. At Fira (**a**) the thickness of the first layer is 5 m, at the site where the trees were found (**b**) 4 m, and in the Akrotiri excavation (**c**) 1 m.

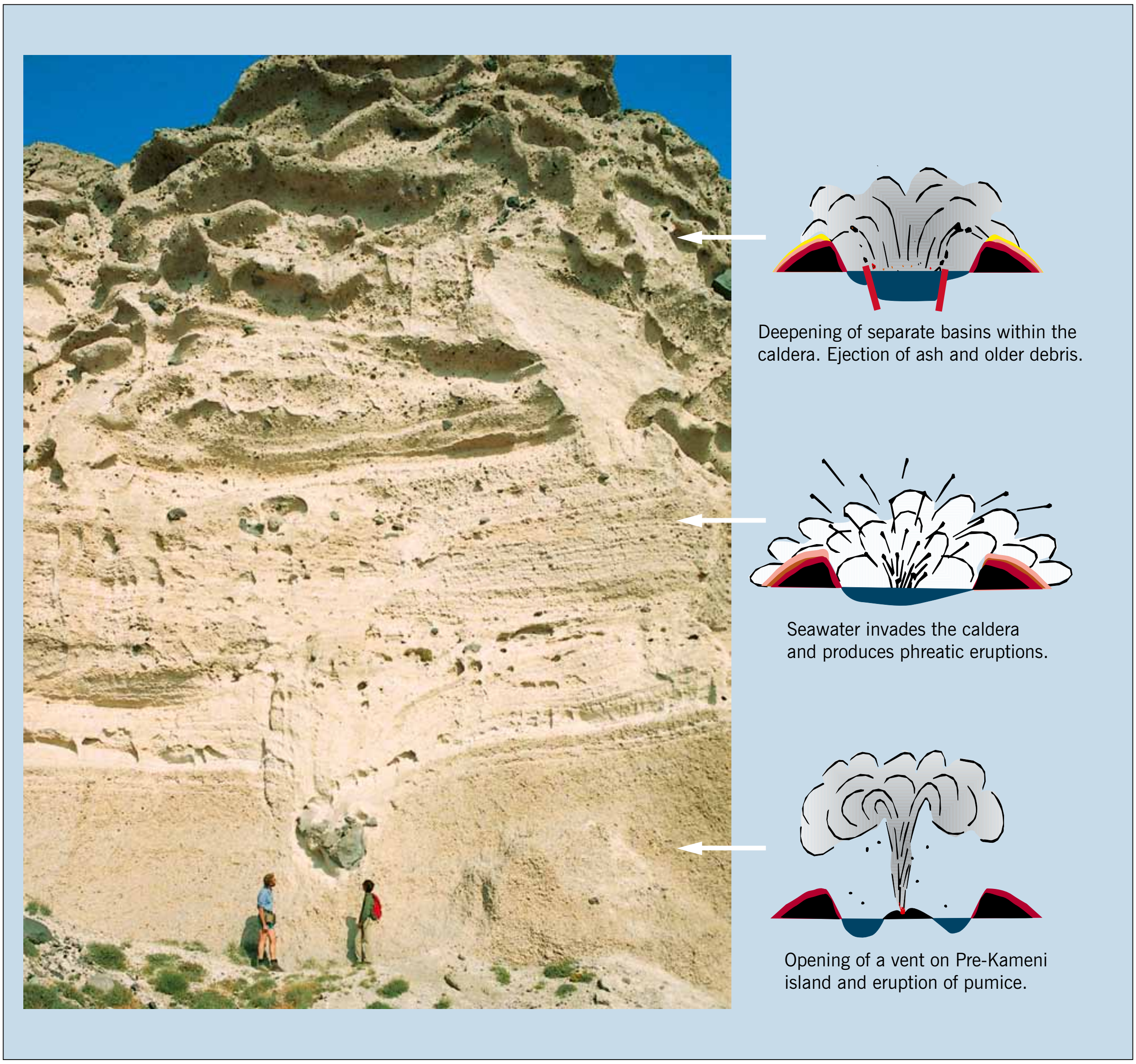

Fig. 8 The diagram to the right shows the three phases of the Minoan Eruption that produced the tuff units in the photo.

the sea east of Santorini. Similar tsunamis were generated by the 1883 eruption of Krakatau. The deep basin in the northern part of the caldera indicates that tsunamis could also have been produced by the collapse of the roof of the magma chamber during the third phase of the eruption. Floating pumice must certainly have hindered shipping and fishing for a long time throughout much of the Aegean. In addition, fine ash particles were carried into the stratosphere where they intercepted part of the sun's radiation and altered the climate on a global scale. This too would have contributed to widespread crop failures and famine (Stommel/Stommel 1985).

Destructions by tsunamis on Crete

For decades, this question has been the concern of scientists, especially in the light of the earlier discovery of the Minoan Culture at Knossos on Crete by Sir A. Evans at the beginning of the twentieth century. Recognizing that a destruction of Knossos occurred at about the same time, i.e. in the Late Minoan IA (LM IA) period, as indicated by the style of ceramics found on Santorini in the 1860s; A. Evans began to speculate about a possible connection between the eruption of Santorini and the destruction of Knossos. S. Marinatos (1939), who also worked on Crete, generated much discussion by proposing the hypothesis that the demise of the Minoan Culture on Crete was a consequence of the eruption of Santorini. According to his explanation, the eruption was associated with strong earthquakes, which could have caused great damage to the Minoan settlements on Crete. Moreover, the settlements on the northern coast of Crete would have been very devastated by tsunamis triggered by the eruption. He cited as a documented analogy the eruption of Krakatau in 1883, which had many similarities to that of Santorini. Today it is thought that Crete was spared the most severe effects of the widespread ash fall. Only the eastern tip of the island was covered with a few centimetres of pumice.

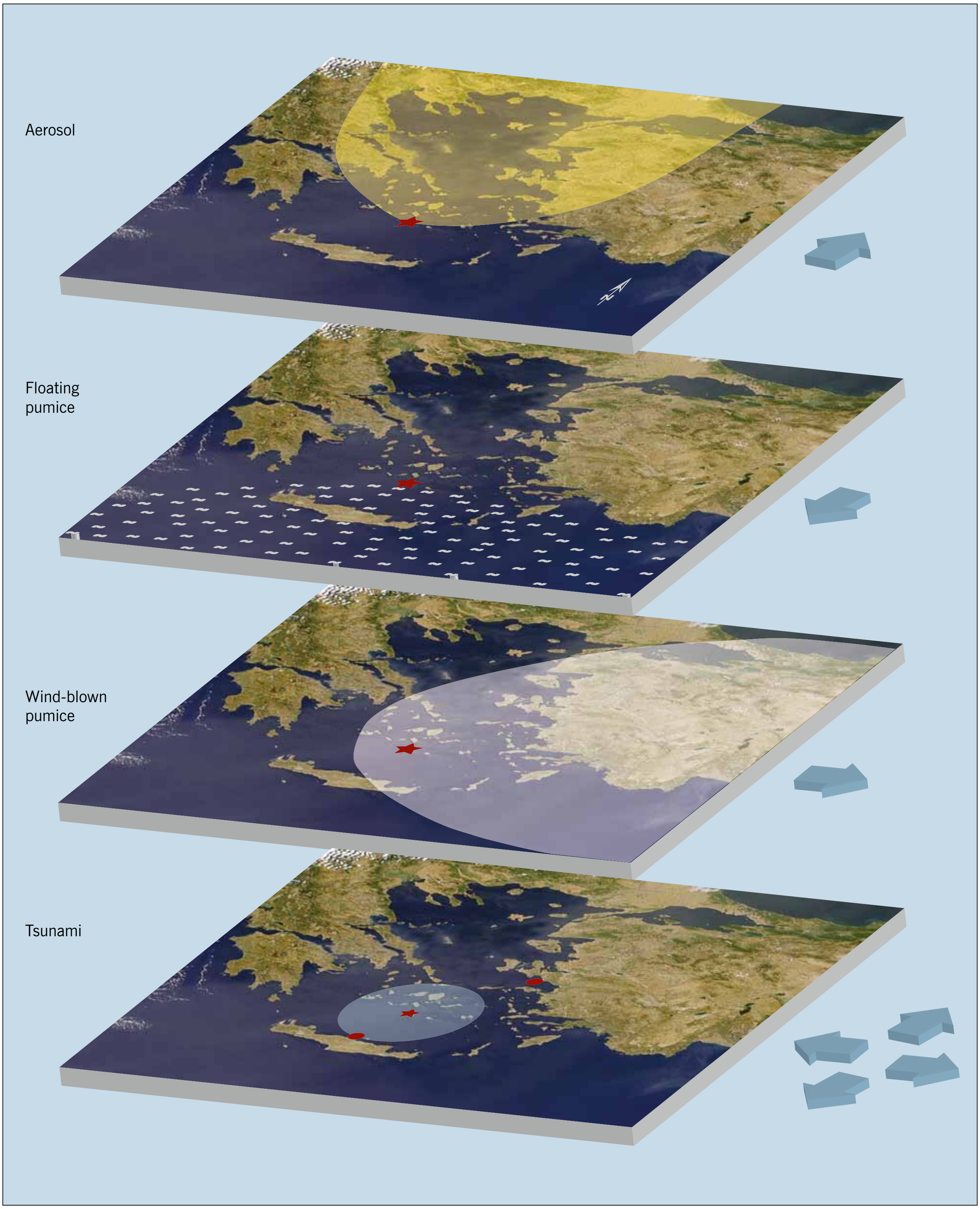

Fig. 9 The diagram shows the effects and distribution of the products Minoan Eruption.

At Mochlos, Pseira and Palaikastro, up to 15 cm of pumice were observed in context with LM IA pottery, thus marking the end of that period. However, recent investigations show that Crete was severely damaged by tsunamis triggered by the eruption of Santorini. In fact, traces of tsunami devastation were observed at Pseira (Betancourt 2009), Palaikastro (Bruins et al. 2008), and Papadiokambos on the northeast coast of Crete (Brogan/Sofianou 2009). At the last mentioned site, both tephra and pumice were observed in connection with LM IA ceramics, but the widespread devastations there are considered to be caused by earthquakes rather than by tsunamis. Since the Minoans were traders, the majority of the population lived in towns close to the coast. This population must have suffered a severe loss. A comparison with the tsunami catastrophe in Sumatra on 26 December 2004 shows us that 80 % of the population died. High floods would have overwhelmed at least the north-coast harbour at Amnissos, one of the ports serving Knossos. It is unlikely, however, that the palace of Knossos was destroyed by tsunamis, because it has an elevation of about 60 m above the sea. In the lower parts of the northern coast of Crete the coastal settlements were wiped out. Ships anchored there would have been destroyed or carried inland by the waves. To explain the destruction of towns situated higher on Crete, however, one must look to other devastating events, such as powerful earthquakes and fires (Pichler/ Schiering 1977).

Some scholars have concluded that the Mycenaeans of mainland Greece had conquered the weakened settlements, but internal political problems could also have brought about the collapse of the Minoan civilization.

Conclusion

The Minoan Eruption of Santorini was strong enough to devastate major areas in the eastern Mediterranean. Mainly the first eruption phase laid a big ash-fan over the islands east of Santorini and over a major part of Anatolia. This phase could have triggered global climate changes and could have devastated harvests in the areas hit by the ash fall. As a result, people had to leave their home areas. There is historic evidence that during the reign of King Chieh around 1630 B.C., climatic deterioration was registered even in China (Pang et al. 1989). In the following two phases, the volcano ejected so much pumice that it covered the surface of the sea and made all navigation in the surroundings of Santorini for a long time impossible – as evidenced for instance in a smaller eruption of Kolumbos Volcano near Santorini in 1649–1650 A.D. (Ross 1840). The three eruption phases may have been followed by tsunamis that had the potential of causing catastrophic damage on the coastal areas facing Santorini. The main tsunami, however, was triggered when the roof of the magma chamber collapsed. Recent tsunami catastrophes[4] have shown that several tsunamis often follow each other in a short time interval. This might also have been the case with the Minoan tsunamis. Since the Minoans were traders – both in the Cyclades and on Crete – most of their villages and harbours facing Santorini were hit by the devastating tsunamis. Waves of up to 28 m (McCoy 2008) carried the fleet onto land where it was smashed in the mountainous landscape. Also foreign trade vessels that happened to be in the area might have suffered the same fate, which would mean that this major catastrophe could have had a strong influence on trade relations and cultural development in the whole region. The loss of the fleet and of a great part of the population of the coastal areas must have led to a severe disruption of trade, at least for a few generations. As a result, new traders were given the opportunity to enter the market.

Abbreviations

DYE 3	Ice Core Site (in the context of GISP)
GISP	Greenland Ice Sheet Project
(N)GRIP	(North) Greenland Ice Core Project
VEl	volcanic explosivity index
LM	Late Minoan

4 E.g. Sumatra, Dec. 26, 2004; Japan, March 11, 2011.

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