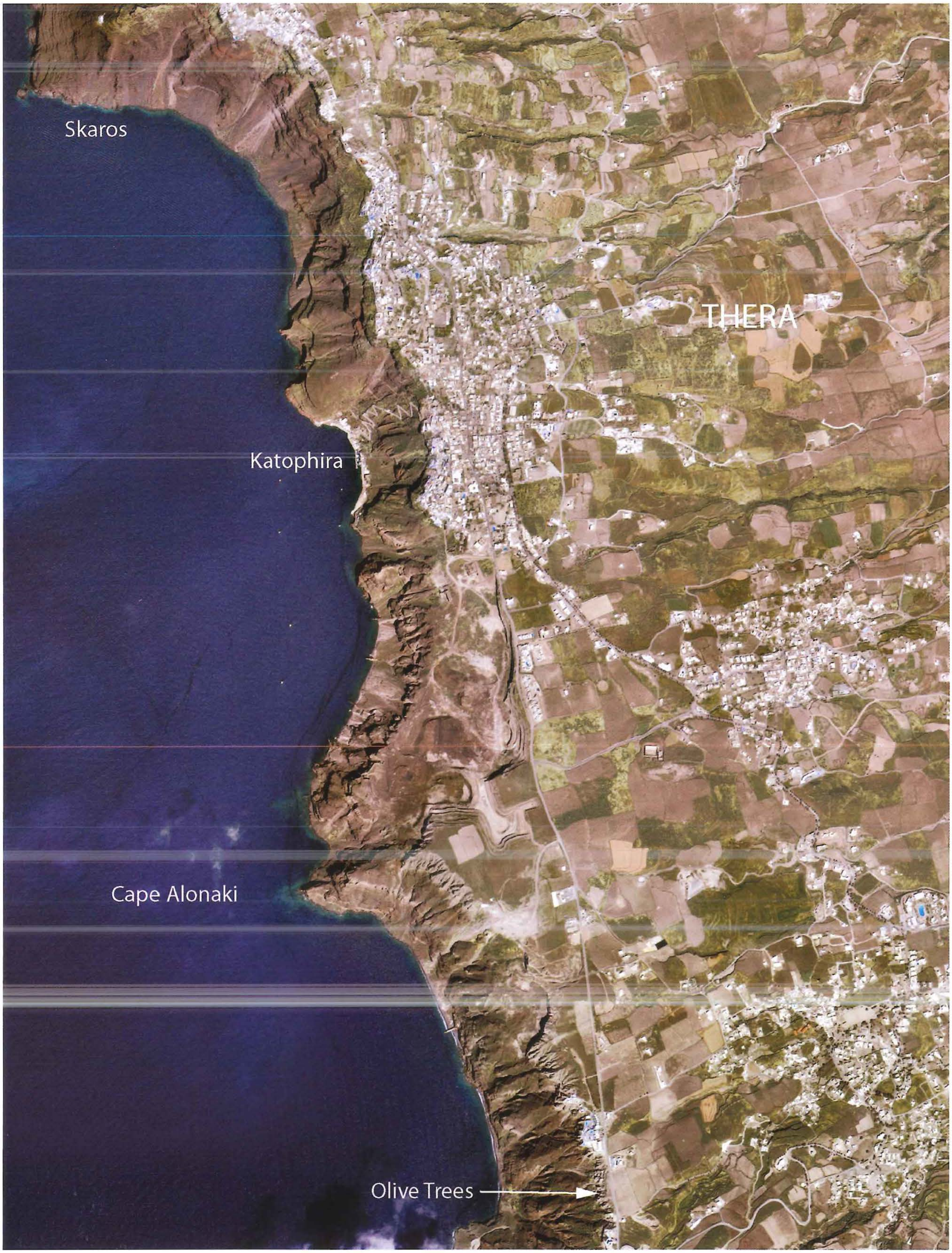

Fig. 1. The arrow marks the locality on Thera where the trees were found. Satellite photo: European Space Centre.

The Minoan eruption of Santorini radiocarbon dated to 1613 ± 13 BC – geological and stratigraphic considerations

Walter L. Friedrich & Jan Heinemeier

Summary

The Bronze Age (Minoan) eruption of Santorini is one of the strongest experienced by mankind. Its enormous strength was a result of a long period of volcanic inactivity. This is evidenced at the excavations at Akrotiri and the Potamos Valley. It is also true of the site on the caldera wall where two olive trees were found (Fig. 1); buried alive by the eruption, the first tree provided a high-precision radiocarbon date, the most direct radiocarbon date for the eruption: 1613 ± 13 cal. BC. (See Heinemeier *et al.* this volume).

The eruption spread a huge fan of tephra (pumice and ashes) over the eastern part of the Mediterranean. The tephra provides a valuable time marker: all objects that are in direct and undisturbed contact with the tephra are synchronous. Thus, the dating of the tephra layer is of paramount interest for the chronology of the Aegean world, Egypt and the Levant.

Introduction

The current state of the Santorini archipelago is partly the result of the Minoan eruption of Santorini (*cf.* Fig. 2 for the current, post-eruption, state of the island; Fig. 3 for the pre-eruption state). This spread material over a large part of the eastern Mediterranean (McCoy this volume, Fig. 6), and the archaeological material found on the island has parallels throughout the region. For decades, scholars have been searching for a precise and direct date for the Minoan eruption of Santorini. Should the tephra layer produced during the eruption be clearly identified in archaeological contexts elsewhere in the Eastern Mediterranean, it would be a valuable time marker for stratigraphic sequences with

Fig. 2. Map of Santorini with localities.

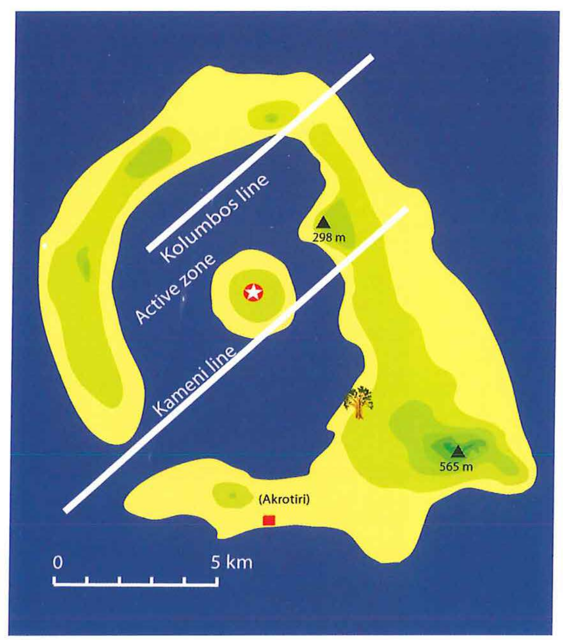

Fig. 3. Reconstruction of the shape of Santorini prior to the Minoan eruption. The tree symbol marks the site where the olive trees were found. The thick lines define the active volcanic zone where emanations of gases occurred.

Fig. 4. A. Shows the locality on the caldera wall where a second olive tree was excavated in July 2007. Circles mark the sites where roots were found. B. Shows the excavators with the 183 cm long branch. C. Olive leaves are found in the fine pumice dust in the precursor layer (see arrow in A). D. The rectangle marks the area that was sampled for radiocarbon dating.

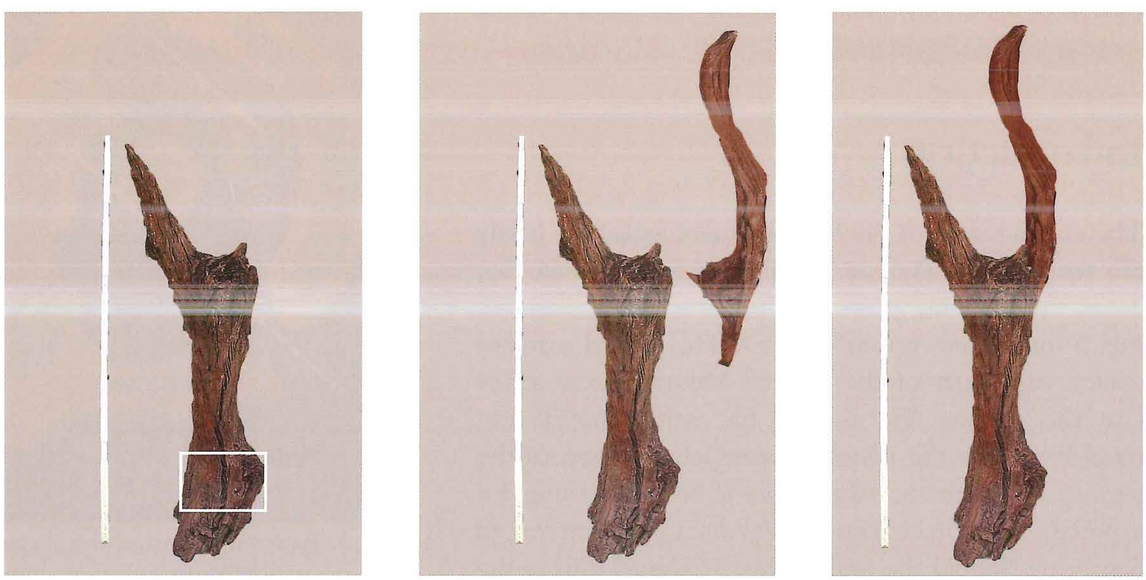

Fig. 5. The first olive branch was excavated in 2003 (left). In 2007 the continuation of this branch was found (middle) and the right picture shows how the two parts fit together. The rectangle marks the area that was used for X-ray investigation and radiocarbon dating (see frontispiece opposite title page).

architecture and objects in direct and undisturbed contact with the pumice.

Obviously, dating the layer absolutely would depend upon a direct date for the Minoan eruption of Santorini, hitherto dated only relatively through pottery sequences. Thus scholars have been seeking organic material for radiocarbon dating this catastrophic eruption. In 1958, Galanopoulos was the first to use charred wood from the quarry south of Phira on Thera for this purpose. The excavations at Akrotiri started in 1967, and as the work progressed, grains found in the storage vessels were used in the dating process. The results of the radiocarbon dating indicated an offset of roughly a century or more (depending upon the argument) from what was expected by archaeologists, based on their estimates of the dates based on archaeological and historical sources. However, the first radiocarbon data were based on samples which were too small, or on uncertain stratigraphy. Besides, the calibration curve of that time showed a plateau which hampered calibration so that precision was lost. And, in any case, only seeds and other short-lived material were found in the Akrotiri excavation. Wooden items such as furniture and beams had rotted away, except for a small fragment with about 10 year rings that could be identified as *Tamarix* sp.[1]

The first olive tree

Therefore, it was a lucky incident when Tom Pfeiffer discovered the branch of an olive tree buried alive in the pumice of the Minoan eruption (Figs 4-5).[2] This unexpected find changed the whole situation: For the first time, we had a tree that was directly connected to the event of the eruption, giving us a chance to find the last growth ring which had been formed in the year of the eruption.

In 2003 a one meter long branch of a tree was extracted from the tephra, and the distal end of the same branch, 90 cm long, was found in 2007 (Fig. 5). The main stem of the tree has disappeared into the caldera due to erosion of the caldera wall. The presence of olive leaves, together with the characteristic shape of the branch, indicate that it was an olive tree. The roots found in a soil of strongly weathered volcanic tuff showed that the tree had been buried alive *in situ*. The preservation of the roots was, however, very poor, as they were reduced to black organic dust.

The date

It was this first tree which provided the high-precision date. Using 3D X-ray tomography it was possible to count 72 year rings (see frontispiece oppisite title page), and the rings were sampled in four groups. In this fashion, the mean radiocarbon age of each group of rings could be placed on the IntCal04 calibration curve, resulting in the final calibrated age range 1627-1600 BC (1613 ±13 BC) with a probability of 95%.[3]

The second olive tree

The first branch was found in 2003, and in 2007 another tree was excavated only nine meters away from the first one. The locality was situated on the caldera rim at a height of 150 meters above sea level. The second tree was discovered in June 2007 when Tom Pfeiffer noticed a nearly hemispherical cave at the bottom of the pumice of the first phase of the Minoan eruption. The cave was about one meter deep and 70 cm high, with a piece of seemingly charred wood protruding at its very top. By cautiously digging away the pumice in July 2007, we recovered a branch 183 cm long and 13-15 cm across. Olive leaves were likewise found here in the 4 cm thick precursory layer of the eruption, along with roots in the ground (see Friedrich & Sigalas this volume, Fig. 13). In addition, smaller side branches and a continuation of the main branch were observed; as the cave increased in size as we removed more and more loose pumice. Eventually, it was enlarged so that a person could stand upright in it, but we realized that it would be too dangerous to continue our digging. Consequently, the small-

[1] Friedrich *et al.* 1990.
[2] Pfeiffer 2003.
[3] Friedrich *et al.* 2006.

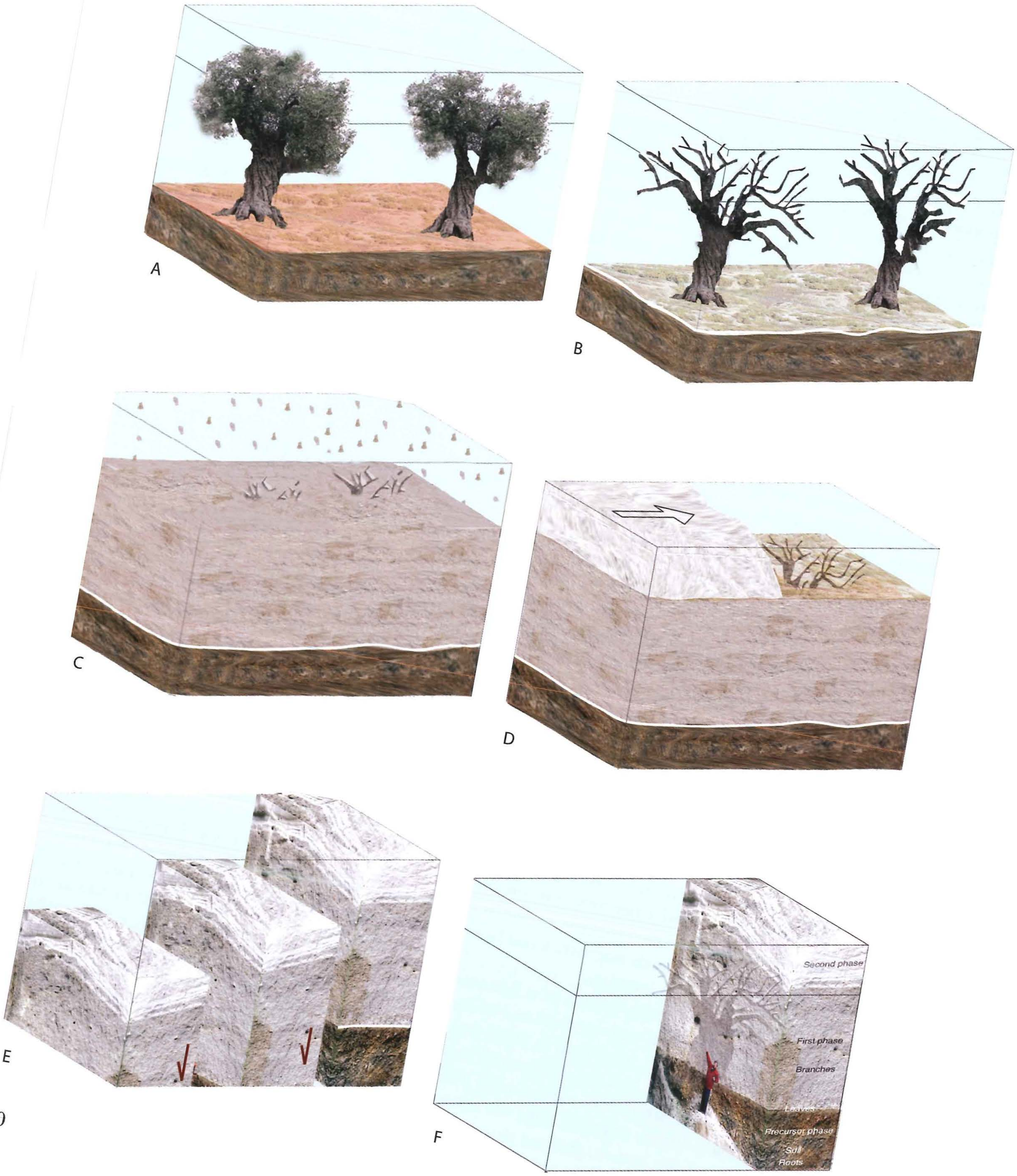
A
B
C
D
E
F
Second phase
First phase
Branches
Leaves
Precursor phase
Soil
Roots

Fig. 6. (opposite). A. Two olive trees growing close to a man-made Bronze Age wall. B. In the initial phase of the eruption the south-western part of the ring island (Akrotiri Peninsula) was hit by a hot volcanic blast. As a result, the leaves of the trees dried up immediately. They fell down and were embedded in the white pumice dust covering the surface. This precursor layer is only 4 cm thick. C. In the first phase of the Minoan eruption, falling pieces of pumice almost covered the olive trees with a 4 meters thick pumice layer. The still warm pumice charred the trees. D. The second phase of the Minoan eruption produced ring-shaped clouds of gas and pumice in an expanding suspension that moved radial away from the crater with high velocity. The uppermost branches of the trees that were not covered by the pumice of the first eruption phase were cut off by the horizontally directed blasts (base surges). E. After the third phase of the Minoan eruption the caldera wall was unstable, and as a result huge blocks of the wall became detached and slid down. Thus most of the charred olive trees disappeared, leaving behind only a few moulds with branches. F. Present situation on the caldera wall showing the moulds with branches. The 4 cm thick white layer of pumice dust (Bo0) contains olive leaves. Moulds and vestiges of the tree roots are found in the soil. They are not charred, because they were protected from the heat by the soil.

er side branches and the continuation of the main branch were not taken out.

As a Bronze Age wall was discovered only a few metres away (see Heinemeier *et al.* this volume, Fig. 2), and a piece of Akrotiri style pottery was also found here by N. Sigalas, it seems reasonable to propose that the two trees might have been part of an olive grove close to a settlement on the caldera rim. The second branch is presently undergoing radiocarbon analysis in Heidelberg and Oxford.

How were the olive trees buried in the pumice?

The trees were found *in situ* at an elevation of 150 meters above sea level on the present day caldera wall (Figs 1 and 2). The site is about 3.5 km south of Phira (36°23'32 N 25°26'17 E).

Santorini's appearance in the Late Bronze Age was similar to that it has today (Fig. 2). The islands we see today, Thera, Therasia and Aspronisi, formed a nearly closed ring that was open in the southwest, and in the centre was a volcanic island, the Pre-Kameni Island (Fig. 3). The present day Kameni Islands did not yet exist, since they were formed during the past 2000 years. This reconstruction (Fig. 3) is based on the discovery of stromatolites and other geological observations. The stromatolites (colonies of algae/bacteria) were found in the pumice of the third phase of the eruption. Originally, the stromatolites grew in shallow brackish water in the centre of the ring shaped island. They were thrown out in the last eruption phase.

Vestiges of ruins and vegetation on the old ring island indicate that it must have been inhabited. Numerous archaeological finds of pottery sherds and ruins of buildings on Thera and Therasia show that there were several settlements on top of the ring island. Remnants of trees were discovered on Therasia and in six localities on Thera, including the Akrotiri excavation. Thus, we have a basis for proposing a reconstruction of the effects and course of the eruption (Fig. 7), and the fate of the olive trees (Fig. 6).

The olive trees that will be presented in the following were growing on a terrace on top of the caldera wall. The settlement might have been in the neighbourhood, as the above-mentioned wall indicates. The proximity of the two trees indicates that they might have been planted at the same time, and that they reached an age of at least 72 years. This can be deduced from a ring count of the branch of the first olive tree.

The mechanism of the Minoan eruption

The catastrophic Minoan eruption hit the olive trees that were growing on top of the then contemporary caldera wall in a fashion similar to that which buried the settlement at Akrotiri.[4] Here, we

[4] See Friedrich & Sigalas this volume.

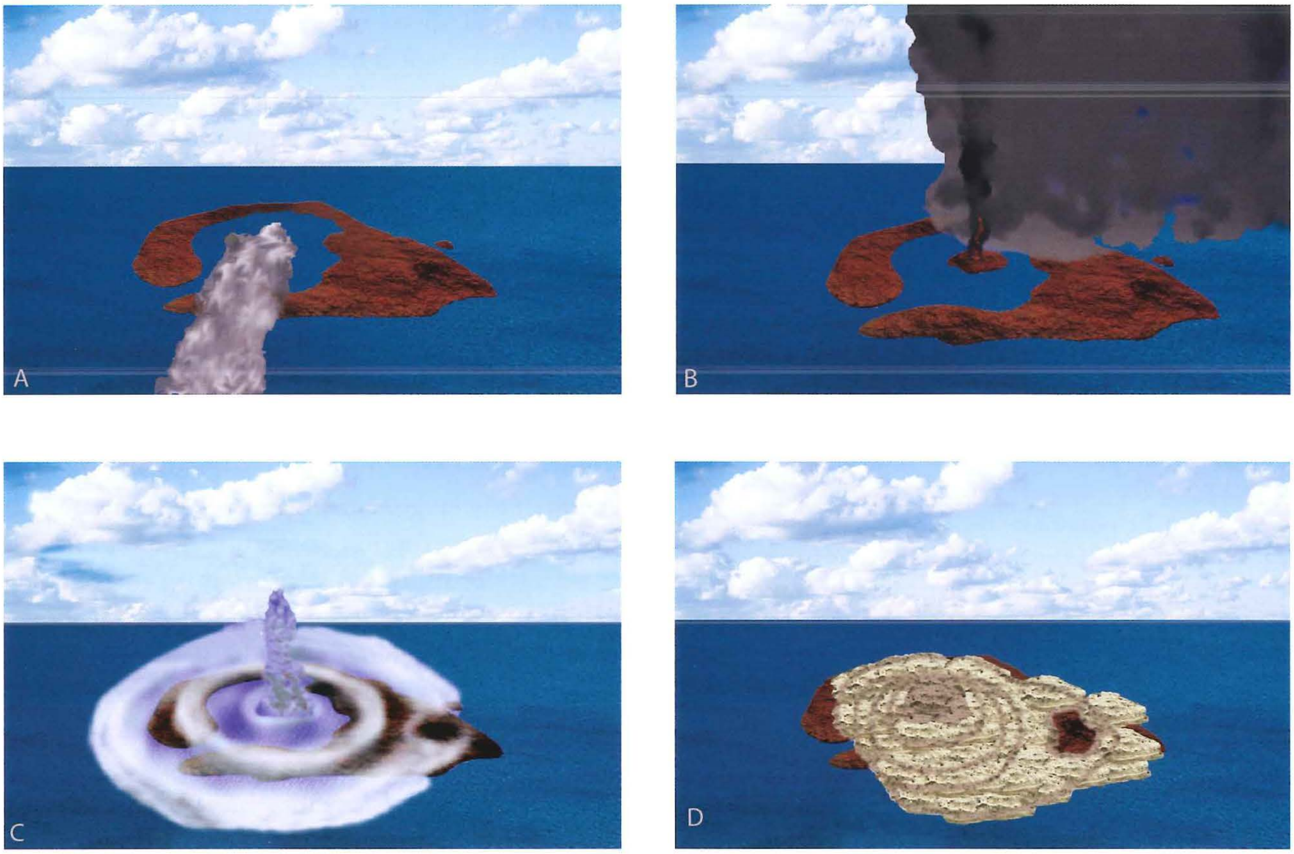

Fig. 7. A The precursor blast hit only the Akrotiri peninsula. At the site where the olive trees were found it deposited 4 centimetres of fine pumice dust. In the Akrotiri excavation the precursor layer is 7 centimetres thick. B The first (Plinian) phase of the eruption started within the caldera, where the Pre-Kameni Island was situated at that time. The eruption column in this phase is thought to have reached an altitude of about 40 kilometres. C In the second phase of the eruption hot magma and seawater got into contact resulting in base surges. D In the third phase the roof of the magma chamber collapsed and huge masses of sea water rushed into the crater that re-emerged and covered almost the entire island with pumice and ashes.

provide a short overview of the mechanism of the eruption (Fig. 7 A-D) to facilitate understanding how and why the olive trees were preserved in the pumice of the eruption.

The precursor phase of the Minoan eruption (A) – Earthquakes were among the first signs of the coming eruption, evidenced by the ruins of houses found in the excavation of Akrotiri. They were followed by a precursory explosion that produced a fine layer of white-yellowish pumice dust that hit the olive grove on the caldera wall and the Akrotiri site, leaving behind a 4 cm thick blanket of pumice powder on the olive tree locality. In the Akrotiri excavation it is 7 cm thick. This layer is only found on the southernmost part of Thera (Akrotiri peninsula).

The first phase of the eruption (B) – The first phase started on the pre-Kameni island and its eruption column reached an altitude of around 40 km. As evidenced from the thickness of the layer on Santorini we can deduce that wind carried the pumice in an easterly direction. In this phase the pumice covered most of the olive trees still standing.

The second phase of the eruption (C) – The eruption mechanism changed totally in the second phase of the eruption. The eruption crater widened and sea water came into contact with the hot magma. This resulted in ring shaped suspensions of pumice and water that expanded laterally from the vent. Any branches that protruded from the top of the deposits of the first layer would have been subsequently cut off by the deposits of the second phase.

The third phase of the eruption (D) – In the third phase, the roof of the magma chamber collapsed and huge masses of seawater rushed into the widened crater. They rushed back and flowed over the caldera rim and down the slope where they entered the sea. This phase did not affect the olive trees buried in the products of the previous phases (Fig. 6).

Conclusion

The olive branch is such an ideal sample providing a very direct and precise, tight date based on simple and transparent assumptions, analyzed with well established radiocarbon methodology (calibration). The trees were standing in life position, the wood slightly charred. We consider the date from this branch to be the most solid scientific determination of the timing of the Minoan eruption presently available.