Quaternary pyroclastics from Santorini/Greece and their significance for the Mediterranean palaeoclimate

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Radiocarbon data from four different horizons of the Santorini volcanic pile show that an unusually long period of volcanic inactivity of about 15,000 yr preceded the late-Minoan outburst. Three different plant-bearing palaeosols of about 37,000 yr, 18,000 yr and 13,000 yr B.P. can be correlated with interstadials in eastern Macedonia, deep-sea cores from the Mediterranean and interstadials from the northern hemisphere. Fossil plants from the *Fira palaeosol*, Santorini (~ 37,000 yr B.P.) indicate that the climatic conditions at that time were nearly the same as at present. A similar flora with a corresponding age of about 37,000 yr B.P. also existed on Lipari/Eolian islands, suggesting that this warm period in the Weichselian was widely developed in the Mediterranean area.

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Dedicated to Prof. M. Schwarzbach on the occasion of his 70th birthday.

The Santorini archipelago, which is part of the Cycladian Volcanic Arc (fig. 1), is situated in the southern Aegean Sea and consists of the older ring-islands Thera, Therasia and Aspronisi together with the younger Kameni islets (fig. 2).

The ring-islands are remnants of a single circular island, called Stronghyli, which was inhabited by the Minoan population. In the late-Minoan time, after an interval of about 15,000 yr of volcanic inactivity on Stronghyli, paroxysmal eruptions occurred which culminated in the collapse of the central part of the old island. Thus the Santorini caldera, comprising an area of about 83 km^2, was formed. The eruptions produced a thick pumice layer, reaching a thickness of up to 60 m south of the town of Fira, called the Upper Pumice Series (or Bo, abbreviated from the German term "oberer Bimsstein"; Neumann van Padang 1936). This striking top layer on the ring-islands consists of air-fall pumice and base surge deposits, overlain by thick pyroclastic flows (Pichler & Kussmaul 1972; Pichler 1973; Günther & Pichler 1973). The Upper Pumice Series buried both an old soil horizon (fig. 2) and late-Minoan settlements on Therasia (Fouqué 1969) and Thera. Such a settlement, not only important from the archaeological point of view, is still being excavated near Akrotiri in the southern part of Thera (Marinatos 1968–1974). The pottery from the excavations near Akrotiri belongs stylistically to the late-Minoan Ia period which according to Marinatos (1971: 410) is ascribed a life of 50 years between 1,550 and 1,500 B.C. Based on this, the age of the initial eruption was proposed to about 1,520 B.C. (Marinatos 1968: 56).

Two radiocarbon ages from carbonized trees found underneath the late-Minoan pumice (Bo) from the quarries near the town of Fira about 7 km from the excavations are published which might indicate the starting point of the late-Minoan eruption: 1) A piece of bark from a tree found together with human teeth and bones and fragments of painted pottery gave a conventional radiocarbon date of 1,420±100 yr B.C. (= 3,370±100 yr B.P.) (Galanopoulos 1958). 2) A trunk of a small carbonized tree still standing upright gave a conventional radiocarbon age of 1,456±43 yr B.C. (5568 halflife) (= 3,406±43 yr B.P.) (Marinatos 1968: 56). Both radiocarbon ages are in excellent agreement with the above-mentioned date based on ceramic findings,

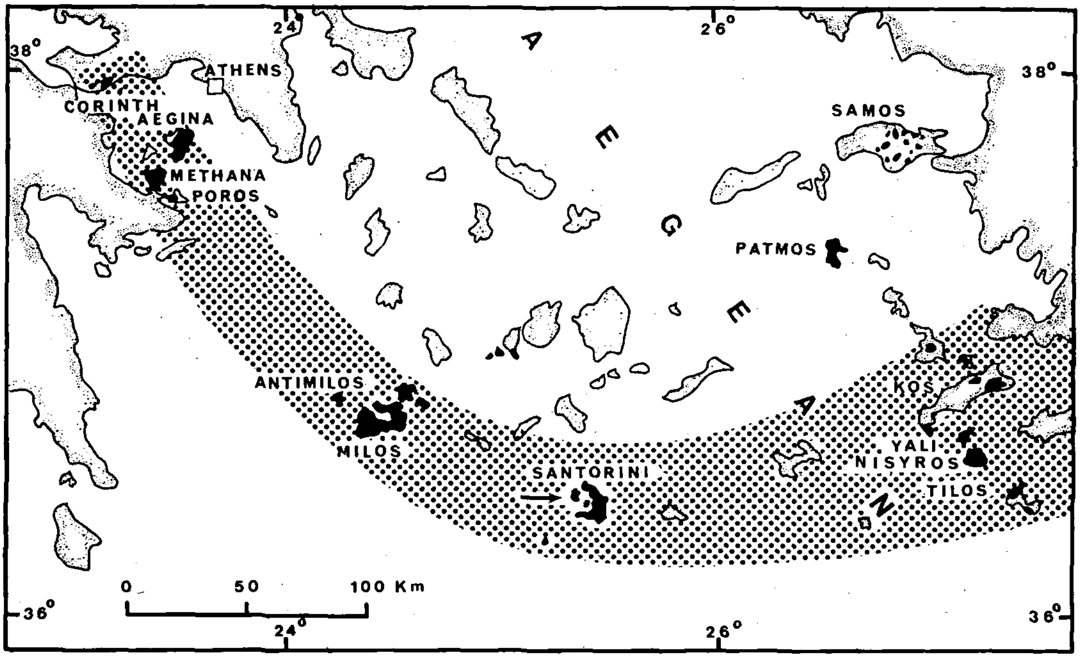

Fig. 1. Geographic position of the Santorini islands in the Cycladian Volcanic Arc (dotted zone). Cenozoic volcanic areas are figured in black.

but if the two radiocarbon dates are calibrated after the tree ring curve of Clark (1975) ages of $1{,}730\pm^{140}_{120}$ yr B.C. (for conv. 1,420±100 yr B.C.) and $1{,}780\pm^{150}_{140}$ yr B.C. (for conv. 1,456±43 yr B.C.) result. This might indicate that the two radiocarbon samples taken from the quarries near the town of Fira may represent a violent earthquake event preceding the late-Minoan pumice eruption.

Since 1939 this late-Minoan outburst of the Thera volcano is widely considered to have caused the decline of the Minoan civilization (Marinatos 1939, 1968–1974; Galanopoulos 1971; van Bemmelen 1971; and many others). Recent investigations on Crete with respect to that problem have given rise to serious doubts to the validity of this theory (Pichler & Schiering, in press).

Ash of this late-Minoan eruption has also been found in many Quaternary deep-sea cores of the eastern Mediterranean. Mellis (1954) was the first to correlate the "Upper Tephra Layer" in the cores collected during the Albatros cruises with the Upper Pumice Series on Santorini. Later on this correlation was confirmed by Ninkovich & Heezen (1965, 1967), Keller & Ninkovich (1972), Ryan (1972), etc.

The stratigraphic sequence underlying the Minoan palaeosol in the central part of Thera island is characterized by at least 21 alternating pyroclastic strata (fig. 4, table 1) which are treated in the following chapter. This sequence rests on the so-called Middle Pumice Series (or Bm, from "mittlerer Bimsstein"; Günther (1972). Below that layer a conspicuous sequence of whitish pumice and ash deposits with an average thickness of up to 80 m is developed (fig. 3). In the profile south of the town of Fira this Lower Pumice Series (or Bu, from "unterer Bimsstein"; Padang 1936) overlies some lava flows of quartz-latiandesitic composition. Most of the strata of that section, from sea-level up to the top (220 m), including the Upper Pumice Series, are products of the Thera volcano, which was the main volca-

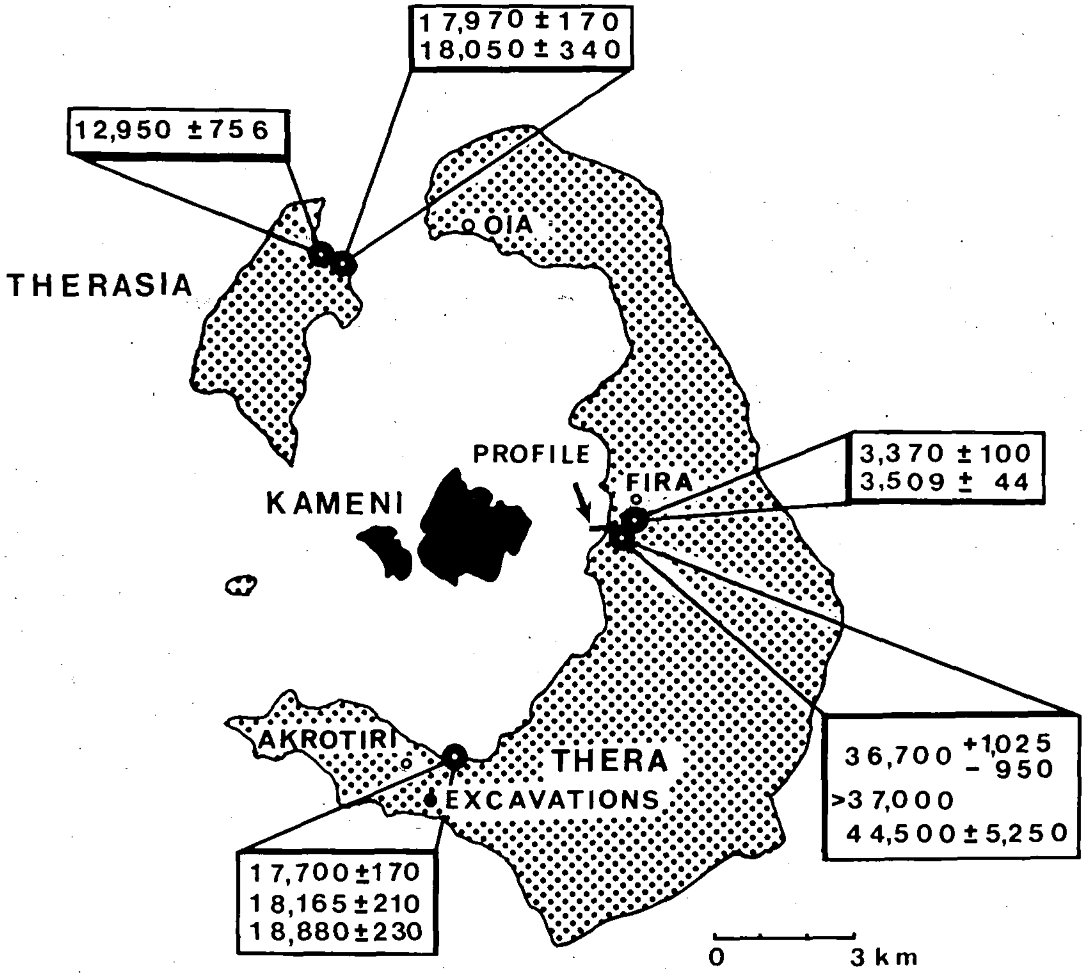

Fig. 2. Radiocarbon dates of Santorini volcanics: location and ages (cf. table 2). The site of the section (fig. 3) is also shown. Dotted areas mark the ring-islands Thera, Therasia and Aspronisi which are almost entirely covered by the Upper Pumice Series. The post-Minoan Kameni islands are figured in black.

nic centre on Santorini. A detailed description of the volcanic history of the Santorini group was given by Pichler et al. (1972); the stratigraphy and petrology of the Lower, Middle and Upper Pumice Series are described by Günther (1972) and Günther & Pichler (1973). New radiocarbon data concerning the upper part of the Thera volcano sequence has been recently published (Pichler & Friedrich 1976).

Pyroclastic Stratigraphy

The upper part of the pyroclastic sequence of the Thera volcano between the Middle (Bm) and Upper Pumice Series (Bo) is excellently exposed at the base of the pumice quarries south of the town of Fira. The sequence consists of at least 21 strata with a total thickness of about 35 m, for the most part comprising dark ashes, cinders,

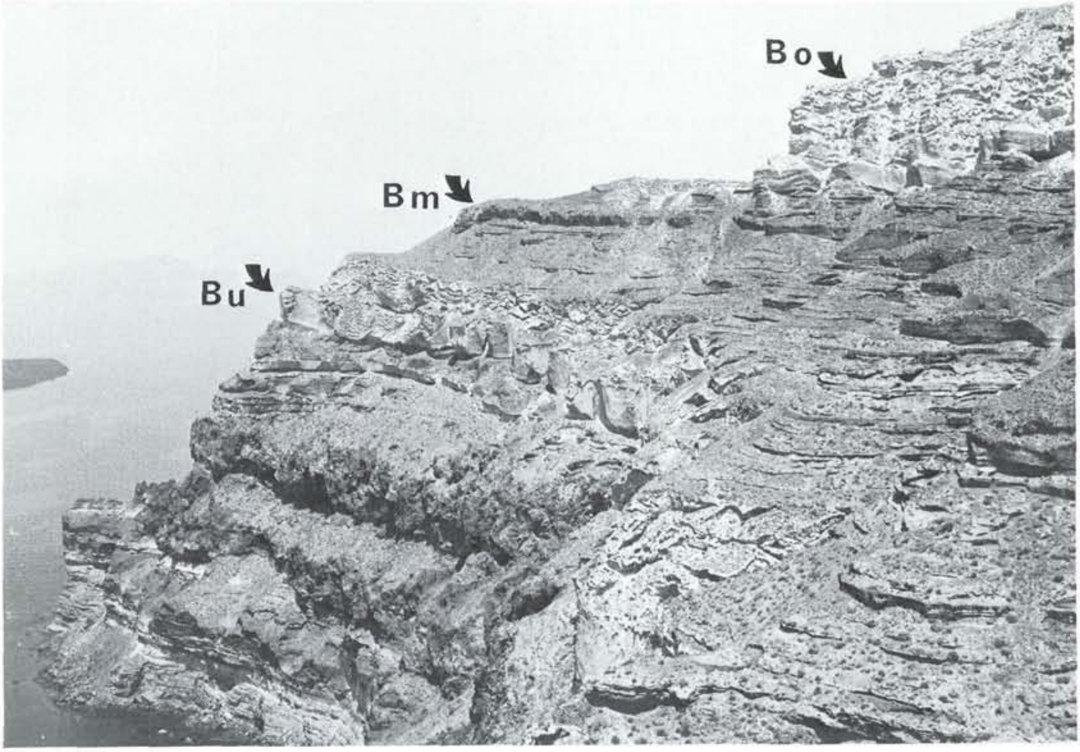

Fig. 3. The caldera walls south of the pumice quarries of Fira/Thera island, Santorini. The sequence corresponds to the schematic section in fig. 4. Bu = Lower, Bu = Middle, Bo = Upper Pumice Series.

scoriae, pumice, bombs, xenolithic lapilli, blocks and lahar deposits (fig. 4). Many of these strata can be subdivided into numerous small beds and horizons. Some of the layers are deeply weathered and decomposed to palaeosols, some of which contain moulds of roots and thin stems of trees and bushes.

Remains of former vegetation have been found in 11 horizons. Four of the strata are rich in plant fossils among which abundant leaves and rarely fruits of the following genera occur: *Chamaerops humilis* L., *Pistacia lentiscus* L., *Phoenix dactilifera* L., and *Olea europae* L. During fieldwork in 1975 and 1976 fragments of a *Tamarix* branch were also found.

Fossil plants from this locality have been known since 1896 when Lacroix mentioned these four genera. In 1936 Schuster described *Ch. humilis* L., *P. lentiscus* L. var. *latifolia* Coss. and *O. europea* L. var. *communis* AIT.

Generally the plant remains are very badly preserved. In the plant horizons of strata 7 and 13 several moulds of *Chamaerops* trees were found (figs. 7, 8) indicating that the palms grew in situ and reached a height of about 2–3 m with a stem thickness of 30–40 cm. The leaves of *Olea* and *Pistacia,* however, have been transported by water, and mostly isolated leaves and small branches can be found. Cuticules are seldom preserved because the organic material is usually totally decomposed. Occasionally small branches and roots have been replaced by whitish material.

The pyroclastic strata, especially the layers Bm, 10 and 3 (fig. 4), are locally deeply intersected by 10–15 m broad erosional channels which are filled with lahar deposits and younger pyroclastic material (fig. 5).

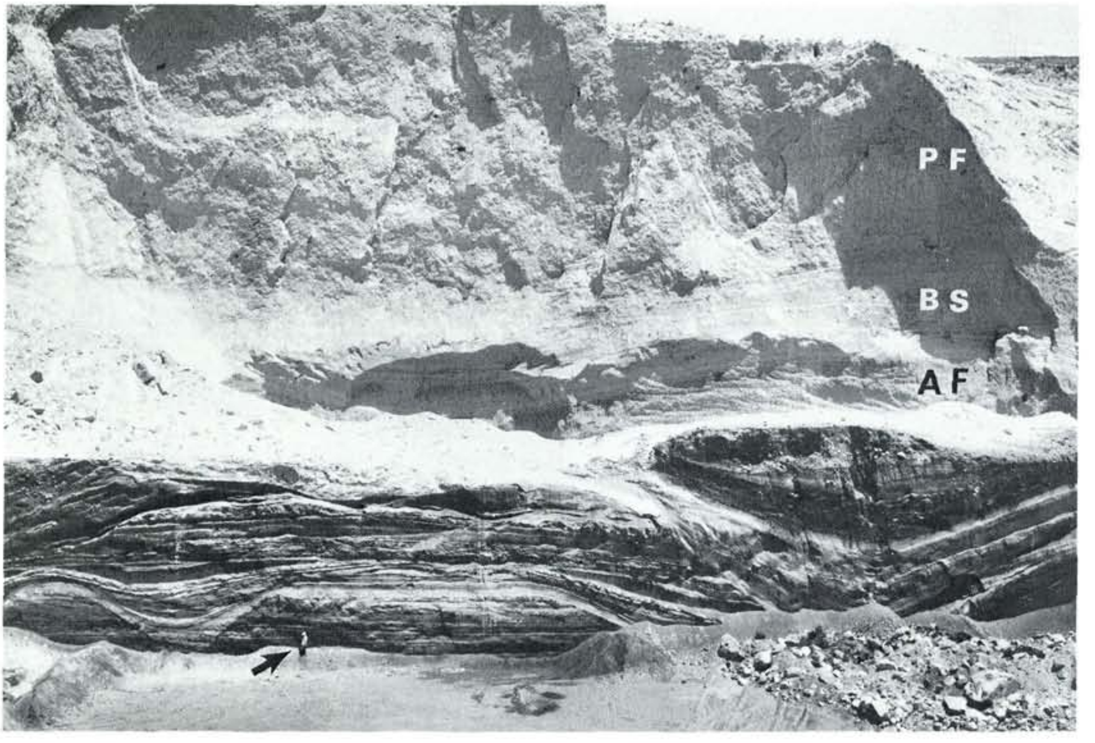

Fig. 5. Section in the pumice quarries south of Fira. The subdivision of the Upper Pumice Series (Bo) into pyroclastic flows (PF), base surge deposits (BS) and air-fall pumice (AF) is clearly visible. The dark sequence, showing some typical erosion channels, comprises the strata 1 to 17 of fig. 4. Arrow marks person for scale.

Radiocarbon ages

The age of strata 1 to 14 can be fixed by way of radiocarbon dates (fig. 4). The late-Minoan outburst, which produced the Upper Pumice Series (Bo), occurred around 1,520 yr B.C. as indicated by ceramic findings from Akrotiri (Marinatos 1968) (see p. 27). The Minoan palaeosol (stratum 1) which is spread all over Thera and Therasia locally reaches a thickness of 3–4 m and contains carbonised plants with an age of about 13,000 yr B.C. (lower part of the Therasia palaeosol on Therasia). This palaeosol rests ùnconformably on ignimbrites which are lacking in the section south of the town of Fira. In the southern part of Thera island, however, these ignimbrites are well developed with a thickness of up to 12 m. They were used by the Minoan people as building-stones, as indicated by the excavations near Akrotiri, where the ignimbrite sheet forms the foundation of this late-Minoan settlement. Charred trees found in the lowermost part of these pyroclastic flows provide radiocarbon ages around 18,000 yr B.P. The ages show that an exceptionally long interval of about 15,000 yr without any volcanic activity on Santorini (Stronghyli) island preceded the late-Minoan outburst. This means that the "Minoan" palaeosol (stratum 1 in fig. 4) represents an interval of the same range, i.e. about 15,000 yr. Consequently, from a volcanological point of view, the old (pre-Minoan) Thera volcano and any other volcanic activity on Stronghyli could be considered totally extinct. The revival of the volcanic events after such a long quiescent interval could not be expected from the volcanological experience and marks an exceptional case.

During fieldwork in 1975 a piece of charcoal, belonging to the *Cupressaceae,* was found in the layer 14. Radiocarbon dating of this sample per-

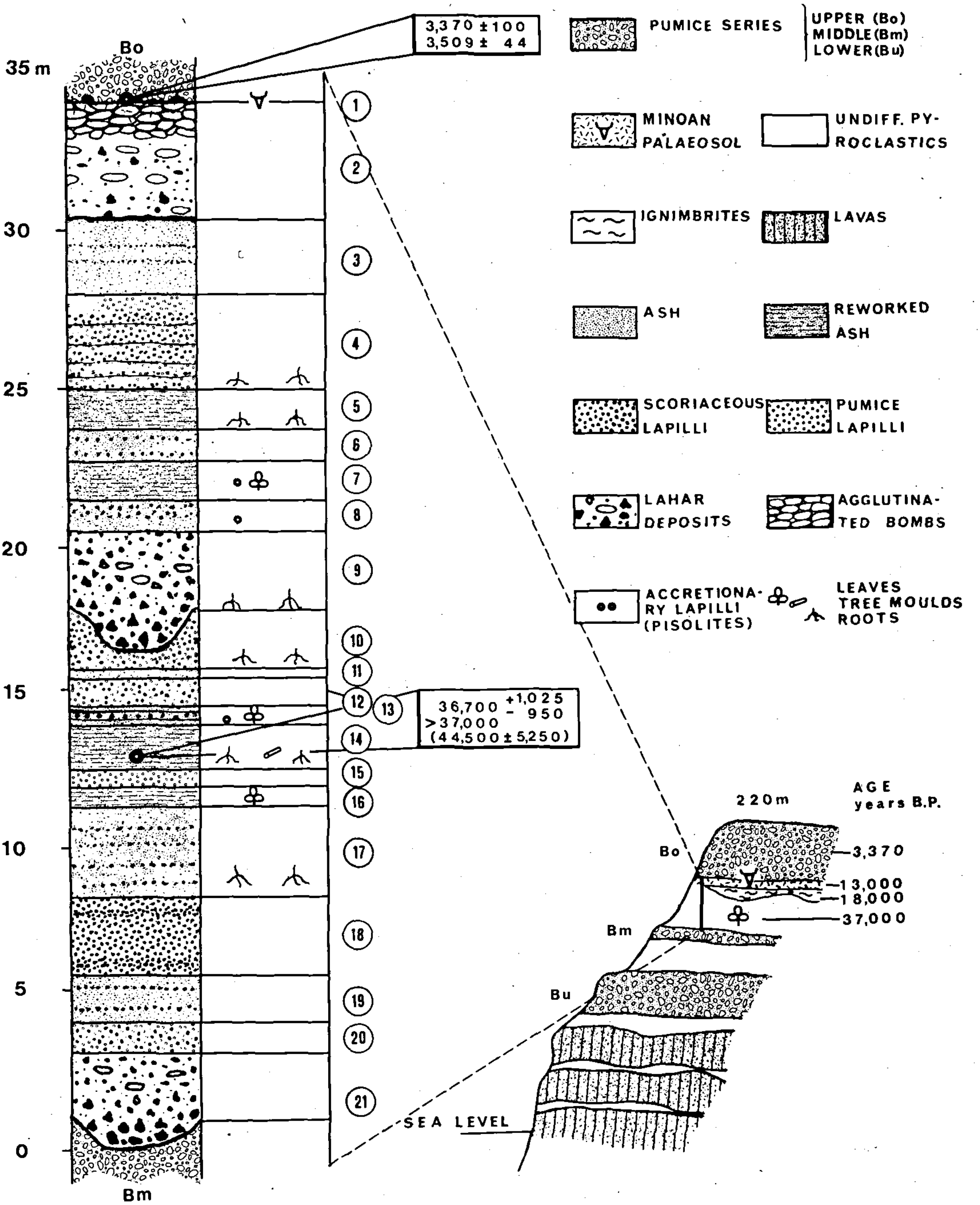

Fig. 4. The stratigraphy and corresponding radiocarbon ages of the pyroclastic sequence between the Upper (Bo) and the Middle (Bm) Pumice Series south of Fira (cf. table 1). The whole profile of the caldera walls south of Fira is drawn schematically to the lower right.

Table 1. Stratigraphic description of the pyroclastic sequence between the Upper (Bo) and the Middle (Bm) Pumice Series according to fig. 4.

Layer	Average thickness	Lithological, stratigraphical, and palaeontological characteristics
Bo	Up to 60 m	Upper Pumice Series: Upper (main) part: pyroclastic flows consisting of unwelded ashes, pumice and lithic blocks. Middle part: base surge deposits. Lower part: air-fall pumice.
1	0.5 m	Minoan and *Therasia palaeosol* (comprising the interval between ~ 3,500 and ~ 13,000 yr B.P.) [The underlying ignimbrites (~ 18,000 yr B.P., cf. fig. 2) are not developed in this profile].
2	Up to 5 m	Reworked pyroclastic material containing reddish to black agglutinated bombs, up to 1 m in diameter. In the lower part concentration of lithic blocks and blockly debris, in the upper part numerous bombs and large scoriae blocks, partly welded together.
3	2 m	Grey to yellowish ash with some small horizons of black cinders.
4	2.5 m	5 beds of greyish stratified pumice lapilli with small lumps of scoriae. Roots.
5	1 m	Reworked ash, locally with accretionary lapilli and grey hardened beds. Roots.
6	1.1 m	Black scoriaceous lapilli with small blocks of scoriae (up to 6 cm in diameter) alternating with ash.
7	1.2 m	Like 5. Leaves. Single accretionary lapilli reach 2 cm in diameter. Erosional channels (fig. 6).
8	1 m	Dark-grey ashes changing at the top into scoriaceous lapilli. In the lower part accretionary lapilli.
9	Up to 4 m	Lahar deposits and reworked pyroclastic material, rich in lithic blocks and black fused bombs, up to 0.8 m in diameter. Roots.
10	Up to 2 m	Grey pumice lapilli and dark-grey lapilli and dark-grey to black scoriaceous lapilli and scoriae (up to 15 cm in diameter) mixed with xenolithic lapilli. Roots.
11	0.3 m	Light-grey bed of hardened ash.
12	0.9 m	Dark-grey scoriaceous and pumice lapilli.
13	0.6 m	Light-grey hardened bed (characteristic "twin-horizon") consisting of: 0.3 m ash with fossil plants. 0.1 m pumice lapilli. 0.2 m ash with accretionary lapilli.
14	1 m	Brown ash with horizons of black scoriaceous lapilli. Roots and tree moulds (~ 37,000 yr B.P.). Reworked, water-transported, cross-bedded.
15	0.4 m	Brownish pumice lapilli, up to 2 cm in diameter.
16	0.7 m	Reworked grey to brownish ash containing leaves and thin, strongly hardened lentiles. Divided by a horizon of black scoriaceous lapilli.
17	1.8–0.3 m	Brown ash, divided by some beds of black scoriaceous lapilli. Roots.
18	1.8–2.4 m	Black scoriaceous lapilli forming a striking morphological layer. Three sub-units can be recognized (0.8 m; 0.1 m and 1.5 m).
19	1.4 m	Like 17.
20	1 m	Pumice and scoriaceous lapilli.
21	Up to 3.5 m	Lahar deposits, rich in lithic blocks (lower part). Scoriaceous bombs, up to 1 m in diameter are embedded.
Bm	Up to 4 m	Middle Pumice Series: Brownish pumice, up to 0.3 m in diameter, ash and lithic blocks.

formed in three laboratories has shown an age of around 37,000 yr B.P. This means, that strata 14 to 2 in our profile were produced during an interval of about 20,000 yr.

Palaeoclimatic Conditions

Fira palaeosol

All species of the fossil plants from the four plant horizons on Thera still exist among the living plants in the Mediterranean and grow even on the Santorini islands (some of them cultivated). This means that during the formation of layer 14 (corresponding to about 37,000 yr B.P.) the climate in this part of the Mediterranean was similar or nearly the same as at present.

The fossil plants of layer 14 on Thera can be

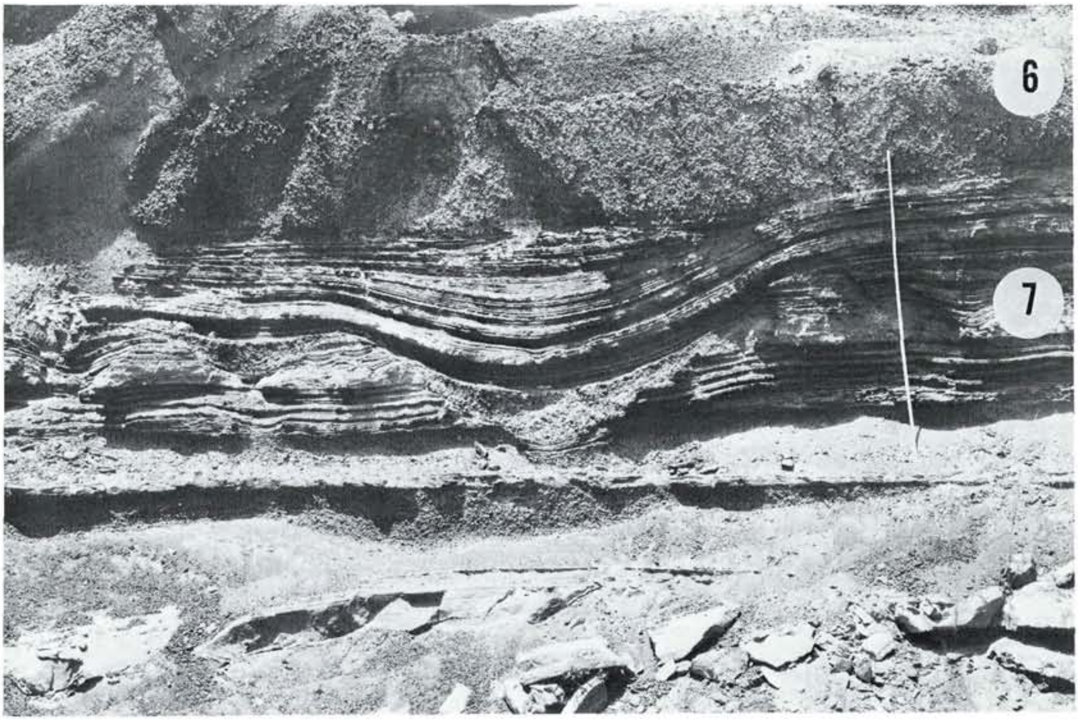

Fig. 6. Detail of the pyroclastic sequence of fig. 4. The small erosional channel in the plant-bearing layer 7 is filled with water-deposited ash. Scale = 2 m.

correlated with the *Kalabaki I* and *II Interstadial* (between 37,000 and 35,000 yr B.P.) which was evidenced by Wijmstra (1969) in eastern Macedonia (northern Greece). Wijmstra demonstrated by palynological investigations that besides the *Kalabaki Interstadial* several other warmer periods alternating with periods of cool and cold steppe vegetation existed in northern Greece (fig. 9). These interstadials correspond fairly well to the interstadials of the Weichselian in NW-Europe.

The plant horizons of the Fira palaeosol on Thera can further be correlated with a plant horizon containing palm-like trees on Lipari/Eolian archipelago north of Sicily. In that horizon charcoal from such a tree gave an age of 39,400±2,000 yr B.P. (Pichler 1968). From other localities on Lipari *Chamaerops humilis* L., *Smilax mauritanica* Desf., Quercus ilex L., Laurus nobilis L., Hedera helix L. var hibernica, leaves of Leguminosae and even *Phoenix* sp. have been found (Gaudin and Mandralisca 1860; Bergeat 1899: 122). Most probably the warm period in the Weichselian at about 37,000 yr B.P., which could be recognized on Santorini and Lipari, is also represented in other parts of the Mediterranean.

Based on a comparative study of planktonic foraminifera in eight cores collected in the Mediterranean it was possible to establish various stages during Würm and postglacial time (Blanc-Vernet 1972). Below the "lower tephra", which has an age of about 25,000 yr B.P., an interstadial lasting from about 42,000–36,000 yr B.P. was found, in which present day climatic conditions could be recognized. This means that the interstadial which is represented by the Fira palaeosol on Santorini and corresponding plant horizons on Lipari was developed throughout the Mediterranean.

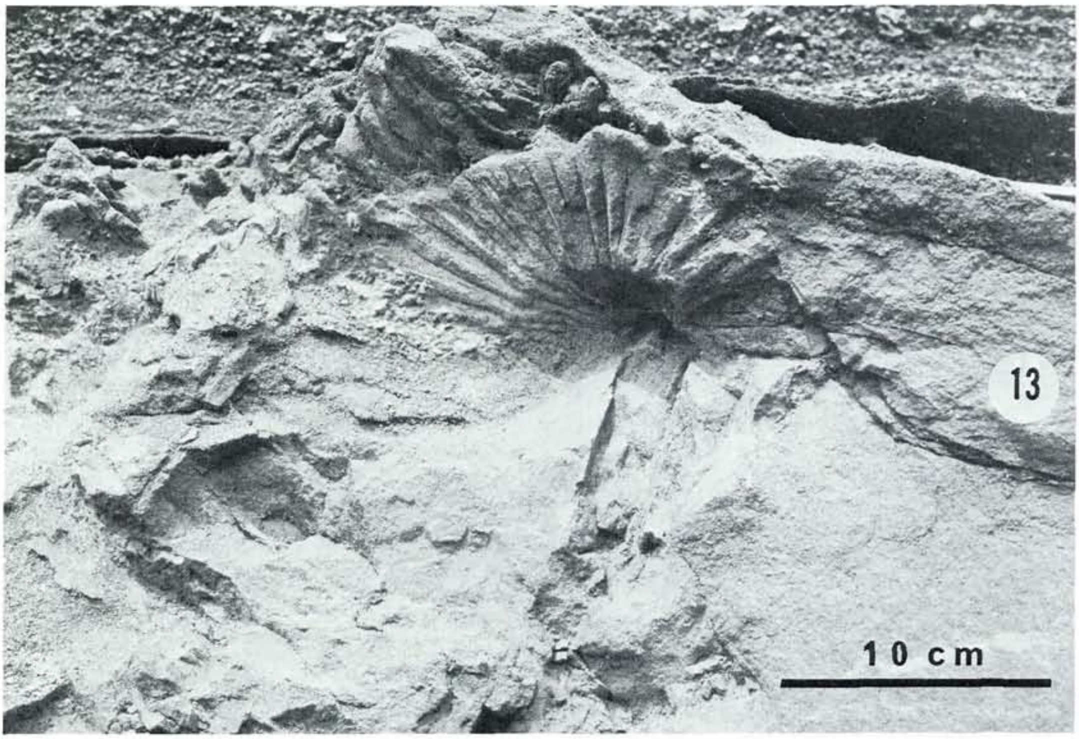

Fig. 7. Upper bed of the "twin-horizon" (layer 13 of fig. 2) with imprint of the dwarf-palm Chamaerops humilis *L. Base of the pumice quarries south of Fira.*

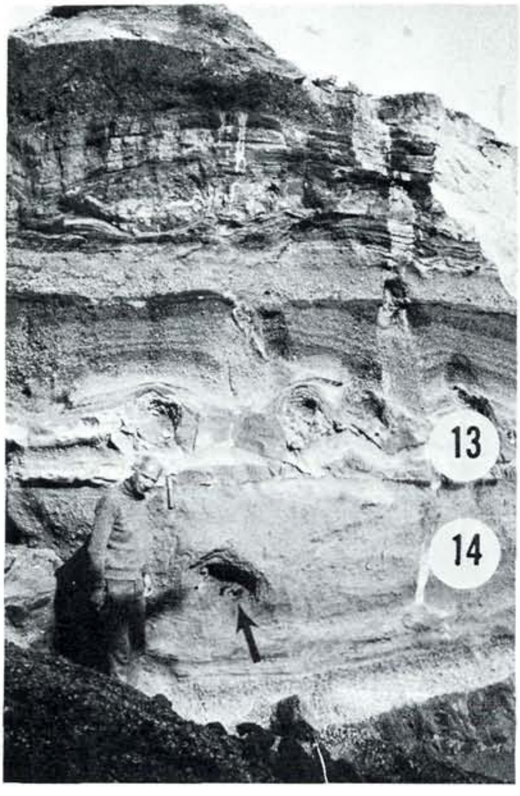

Fig. 8. Layer 13 with tree-moulds of Chamaerops humilis *L. Arrow in layer 14 marks the position of the charred tree with a ^{14}C age around 37,000 yr B.P.*

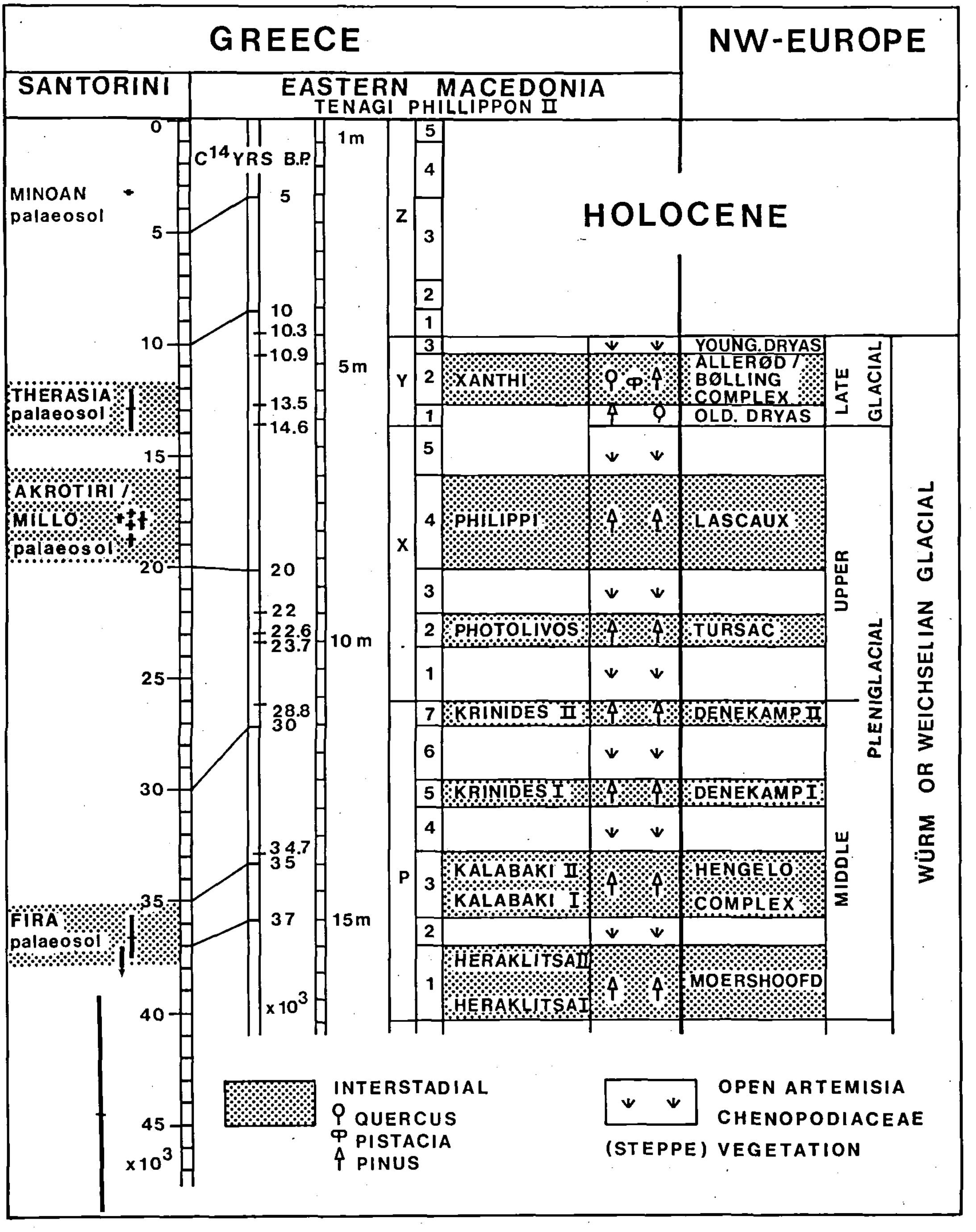

Fig. 9. Correlation of the radiocarbon dated palaeosols of Santorini with interstadials in eastern Macedonia and NW-Europe. Macedonian and NW-European interstadials according to Wijmstra (1969).

Table 2. Radiocarbon data from Santorini volcanics.

Layer (according to fig. 4 and table 1)	Material; locality	Conventional ^{14}C ages B.P.	Reference or laboratory
Bo	Charred wood from the base of the Upper Pumice Series	3,370±100 3,509± 44	Galanopoulos 1958 Marinatos 1968
1	*Therasia palaeosol,* lower part (corresponding to the lowermost part of the *Minoan palaeosol*); Therasia; Millo region (not from »jüngerer Ignimbrit-Horizont« as worngly indicated by Günther & Pichler (1973: 397)	12,950±756	Geochron Laboratories Cambridge (Mass.) USA
Between 1 and 2	Base of the ignimbrite sheet north of Akrotiri (*Akrotiri/Millo palaeosol*)	17,700±170 18,165±210 18,880±230	Niedersächsisches Landesamt für Bodenforschung, Hannover Institut für Umweltphysik, Heidelberg
	Base of the ignimbrite sheet from Therasia, Millo region *(Akrotiri/ Millo palaeosol)*	17,970±170 18,050±340	Niedersächisches Landesamt für Bodenforschung, Hannover Institut für Umveltphysik, Heidelberg.
14	Charred tree, Fira profile (*Fira palaeosol*)	$36{,}700\pm^{1{,}025}_{950}$ >37,000 44,500±5,250	Niedersächsisches Landesamt für Bodenforschung, Hannover Geochron Laboratories Cambridge (Mass.) USA Institut für Umweltphysik, Heidelberg.

It should be noted that the warmer period between about 40,000 and 35,000 yr B.P. was also recognized in some marine sequences of the northern hemisphere, i.e. the *Sandnes Interstadial* (between 42,000 and 28,000 yr B.P.) in southwestern Norway and in Vendsyssel/Denmark (Feyling-Hanssen et al. 1971; Bahnsen et al. 1974; Knudsen in press).

In the *Cape Broughton Interstadial,* Baffin Island, Canada, ranging from about 46,950 yr B.P. to 28,200 yr B.P., the fossil assemblages have an interglacial rather than an interstadial character. That means marine climatic conditions as today or even more ameliorated (Feyling-Hanssen 1976).

Marine deposits from a corresponding interstadial, the *Jameson Land Interstadial* in Greenland, were dated at about 40,000 to 19,500 yr B.P. (Funder & Hjort 1973). Oxygen-isotope measurements on a 1390 m long ice core from Greenland have revealed a detailed climatic record. The climatic curve published by Dansgaard et al. (1970) shows several warm peaks in the interval 27,000–42,000 among which one is dated to 36,700 yr B.P. In the Yenesei area (USSR) the *Karginsk Interglacial,* which includes some warm phases separated by cold periods, ranges from about 50,000 to 25,000 yr B.P. (Kind 1972). For the *Karginsk Interglacial* a climate optimum between about 40,000 and 35,000 yr B.P. has been recognized.

Akrotiri/Millo palaeosol

This palaeosol and its corresponding vegetation was covered by ignimbrite sheets about 18,000 yr B.P. This data is based on ^{14}C determinations (table 2) of five samples of charcoal found near Akrotiri on Thera and in the Millo region on Therasia (fig. 2). It is obvious that the data of about 18,000 yr B.P. correspond quite well to an interstadial in northern Greece (fig. 9), i.e. the *Philippi Interstadial* (Wijmstra 1969). This interstadial, which lasted from about 20,000 to 16,000 yr B.P., is correlated with the *Lascaux Interstadial* in France, and is also recognized in deep-sea cores from the Mediterranean (Blanc-Vernet 1972) and the ice core from Greenland (Dansgaard et al. 1970).

Therasia palaeosol

The ignimbrites with an age of about 18,000 yr B.P. are overlain in the Millo region on Therasia by a 3–4 m thick palaeosol which in its lower part gave an age of about 13,000 yr B.P. The uppermost parts of this palaeosol correspond to late-Minoan time. The oldest parts of the palaeosol which we call *Therasia palaeosol,* can be correlated with the *Xanthi Interstadial* of northern Greece (fig. 9). According to Wijmstra (1969) this period falls between ± 13,500 and 10,900 yr B.P., correlated with the *Allerød-Bølling Complex* in NW-Europe. A corresponding warm period was found in the deep-sea cores from the Mediterranean (Blanc-Vernet 1972).

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Dansk sammendrag

Kulstof-14 dateringer fra 4 forskellige horisonter i den vulkanske lagserie af Santorin vulkanen viser, at vulkanen har haft en hvileperiode på omtrent 15.000 år før det senminoiske udbrud. Tre forskellige planteførende horisonter kan korreleres med interstadialer fra NW Europa, Makedonien og borekerner fra Middelhavet. Fossile planter fra Fira horisonten (palaeosol) fra Santorin, 37.000 år før 1950, viser, at de klimatiske forhold dengang var omtrent de samme som i dag. En lignende flora med omtrent samme alder, ca. 37.000 år før 1950, eksisterede også på Lipari/Italien, hvilket tyder på, at den varme periode har haft stor udbredelse i det mediterrane område.

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