Recent investigations of a Bronze Age eruption (*)

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SUMMARY — The first part of the paper is a short account about the « International Scientific Congress on the Volcano of Thera », organized by the Greek Archaeological Service. In the second part, the author deals with the problem of the so-called Minoan tsunami of volcano Santorin. Some calculations are made concerning the energy of this tsunami in case of different wave-heights. The notion of free tectonic energy is introduced and treated. The author states that the relationship between the height and the energy of a tsunami, expressed mathematically by Iida is useful in the case of the Santorin Minoan eruption, too.

RIASSUNTO. — La prima parte dell'articolo è una breve relazione sul Congresso Scientifico Internazionale sul Vulcano di Thera, organizzato dal Servizio Archeologico Greco. Nella seconda parte l'autore tratta il problema del cosiddetto Minoan tsunami del Vulcano Santorin. Sono stati eseguiti alcuni calcoli sull'energia di questo tsunami nel caso di varie altezze d'onda. Si introduce e si tratta il concetto di energia libera tettonica. L'autore precisa che il rapporto tra l'altezza e l'energia di un tsunami, espresso matematicamente da Iida, è utile anche nel caso dell'eruzione Minoan di Santorin.

Volcano Santorin (Santorini, Thera) is situated in the Aegean-sea, North from Central Crete, 36°24′ N and 25°24′ E about. It is a group of three volcanic border islands and (at present) two

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central islands, one of them still now-a-days is active, in a caldera. The dimensions of the caldera are as follows: diameter in E-W direction is 7,5 km, in N-S 11,0 km; its greatest depth at its northern part is about 390 metres under the sea-level; the height of the walls

Fig. 1 – Map of the islands of Santorin.

in some places exceeds 300 metres. The names of the central islands are Palaea and Nea Kameni; the names of the borderer islands — that are the walls of the caldera — are Thera (the largest part), Therasia and Aspronisi (the smallest part) respectively. The highest point of the Kamenae-islands is about 131 metres above the sea-level. The volume of the caldera under the level of the water is estimated to be about 40-45 km³, that is much bigger than the volume of Krakatoa caldera. The surface of the water inside the walls of the caldera is 83 km². It is generally accepted that during the formation of the

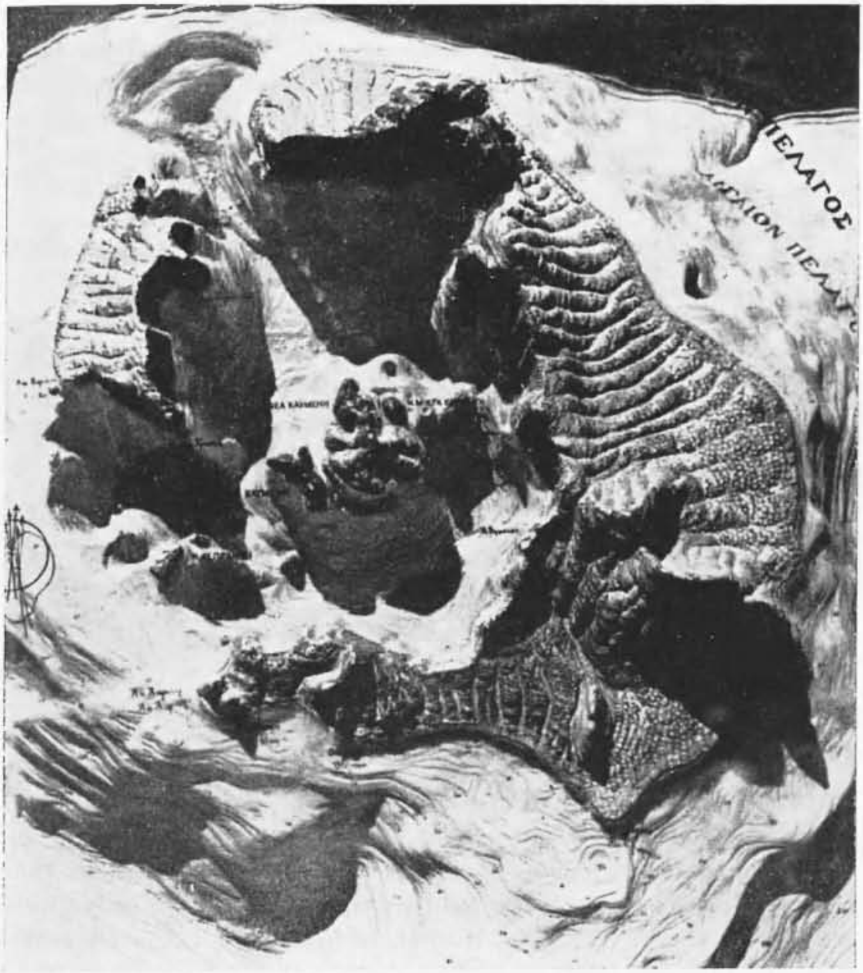

Fig. 2 – Model of Santorin, made on the basis of the British Admirality chart (after *Galanopoulos:* Atlantis. Thomas Nelson and Sons LTD, London, 1969)

Santorin caldera about 72 km³ of material "disappeared" from the surface of the Earth, due in 99 per cent to the collapse phenomenon and in 1 per cent to effective explosions. The lavas of Palaea

Kameni as well as those of the more recent eruptions were first characterized as *andesites with hypersthene and augite* ... Now Georgalas [1] prefers to call the lavas " *dacitoides* ".

Concerning the most ancient eruptions, as far as we can see for them back in the time, Ryan recently stated (Heezen [2]) that a great eruption occurred about 80.000 years ago. According to Heezen and Ninkovich [3] the second catastrophic eruption of volcano Santorin (on its former name: Stronghyle) had taken place in the Bronze Age, at about 1400-1500 years B.C. This latter eruption generally is called as the " Minoan " one, since — according to the archaeological researches, carried out by Marinatos [4,5,6,7] — this gigantic outburst destroyed all the Minoan settlements on Stronghyle itself and many Minoan settlements on Crete, as well as on the neighbouring islands, too.

The formation of the mighty caldera was the direct consequence of this Minoan eruption. At the same time other natural events also occurred: earthquakes, tsunamis and even tornadoes, too [see for instance Galanopoulos [8], van Bemmelen [9], Marinos [10]]. Concerning its intensity, the respective Santorin eruption is comparable with that of some Indonesian volcanoes; Krakatoa in 1813, Tambora in 1815, etc. [11]. The *total energy* released had the order of 10^{27} ergs [12]. I should like to return later to a particular problem of the energy-calculation.

Since the Minoan eruption had an exceptional role in the life and history of the nations in the proximity, as far as all the Cycladic islands to the North, Crete to the South, Egypt and Syria to the Southeast and East respectively, it is understandable that the Greek Archaeological Service decided to organize a great congress with the participation of archaeologists, historians, oceanographers, geographers, volcanologists, geophysicists and other experts. The time of the congress was chosen as September, 1969, since this early-autumn time is very favourable in Greece to take a journey from Athens to Santorin and to Crete by ship. Really, the congress had been taken place between the 15th and 23rd, September, 1969. All the participants were guests of the Greek Governement and of the Greek Archaeological Service which is under the directionship of Professor Dr. h. c. Spyridon Marinatos, member of the Academy. There were about 120 scientists from 16 countries. The lectures had taken place partly in Athens and partly on the ship " Knossos " (10.000 ton). All the papers and the material of discussions are intended to be published as a special " Acta " of the congress. The participants had opportunities to visit the active volcanic centers of the Santorin, where Professor Yokoyama of Hokkaido carried out gravimetric observations, continuing his researches on this subject, as regards the gravity anomalies of volcanic calderas; furthermore to take visits on the sites of recent archaeological researches of Marinatos at Akrotiri (Santorin) and at Amnissos (Crete). We have seen the world-famous Minoan palace at Knossos, Crete as well as some museums, too.

Fig. 3 – The Nea Kameni volcanic island, viewed from East (photo of the author).

The lectures and the discussions dealt with the most different problems. For example: exact time of the Minoan outburst; archaeological explanations of the findings; the tectonics of the Mediterranean; comparison with volcanic eruptions on other parts of the world; effects of the Minoan volcanic catastrophe on Egypt, on Crete and on other lands; energies of the eruption; present problem of lunar volcanism in the light of the Apollo-11 experiment, etc. There was a debate concerning *the height of the Minoan tsunami*. Since it is very important from the point of view of my calculations of energy, I should like to deal with this interesting problem here in its details.

According to Galanopoulos (8): " There is now plenty evidence that the collapse of the central part of the former Stronghyle island was abrupt enough to set up sea-waves of prodigious height that swept clean all the coasts of the eastern Mediterranean. Pumice carried by the sea waves was found in sediments of a post-glacial terrace 5 m

Fig. 4 – Island Thera. In the foreground there is the surface of Nea Kameni. The ship is the " Knossos " of 10000 ton. The town on the caldera-wall is Phera (photo of the author).

above sea level North of Jaffa-Tel Aviv. According to M. Pfannenstiel, the pumice came from the Santorin eruption. Further, archaeological evidence points out that the port and half of the city of Ugarit, in Syria, were destroyed about 1400 B.C. by a tsunami. ... Assuming an eustatic rise of the sea-level by 2 m in the time interval of about 3½ thousand years, the height of the sea waves in Jaffa — Tel Aviv should have been at least 7 m. Disregarding now the loss from absorption and taking into account that the sea waves produced during the birth of the caldera had at a distance of about 900 km a height of more than 7 m, we may easily calculate that their height at the starting point should have been at least 210 m. The calculation of the initial height of the tsunami is in accordance with Marinos' recent estimation [10]. G. Marinos and his associate have found layers of pumice in three places on the island of Anaphi, situated at a distance of about 25 km East of Santorin. ... All these layers were found at the heads of ravines or valleys on the island. Marinos and his as-

Fig. 5 – The edge of the caldera-wall, viewed from the South. The town is Phera (photo of the author).

sociate have good reasons to believe that the pumice on Anaphi was carried by the tsunami following the formation of the volcanic cavity of Santorin ". It is noteworthy that one of these three layers were found 250 metres above the level of the sea, at a distance of 1650 metres from the coast.

M.me D. Vitaliano and Prof. Ch. Vitaliano [13] have argued against this statement, writing as follows: " Inasmuch as Anaphi lies close enough to Santorin to have received airborne pumice in the climatic explosions, the Anaphi pumice must be viewed with reservations as evidence of the height of the Minoan tsunami ".

This may be also true, of course, however I do not share the M.me and Prof. Vitaliano's opinion. As it was mentioned above, namely, *all three layers of pumice were found at the heads of ravines or valleys.* Supposing that the pumice had been carried by the air-shocks, throughout the air, the pumice would distributed over a greater part of the island Anaphi, by and large in the same general distribution. But since the *three* layers were found *just* at the heads of valleys, they had to carried really by the water of the sea alone. This water had been accumulated at the mouth of the valley and reached higher and higher levels during its further way throughout the narrow valley to its upper end. Owing to these considerations I prefer the value of 210 metres as the initial height of the Minoan tsunami, in accordance with the suggestion of Prof. Galanopoulos and Prof. Marinos, respectively. In some of my own calculations I used this value. However I declared that I am willing to repeat the calculations on the basis of other values for the height of the tsunami. I should like to made it here, in the present paper. The following values were chosen: 30 m — corresponding roughly to the tsunami-height after the Krakatoa eruption (*) — 60 m, 90 m, 120 m, 150 m, and 180 m, respectively.

In the course of practical calculation I was forced to use the relationship between the height and energy of tsunamis, established by Iida ([14]) since — as far as I know — special mathematical expression for the tsunamis of volcanic-collapse origin is not exist as yet. I think that the simple relation, expressed as a table in Iida's ([14]) paper is useful in every cases when there is a tsunami in the sea, the maximal height of which is known, — independently from the origin (cause) of the respective sea wave, that is independent from the problem whether it is a wave caused by a crustal deformation of the sea bottom due to a tectonic earthquake or it is a tsunami of volcanic-collapse origin. (See later, too).

(*) During the Krakatoa-tsunami in 1883 the height of sea waves reached a value of about 30-36 metres on the coastal area. According to Iida ([14]) the energy of a tsunami, caused by earthquake, with a height of 32 metres on the coast is about $2{,}56 \cdot 10^{24}$ ergs. It is very probable that a certain part of the energy in the sea wave was transferred to the water from the air wave ([15]). The energy of the air blast in the Krakatoa case was estimated also by Harkrider and Press ([15]) as high as the total explosive energy of a nuclear bomb, equivalent to 100-150 megatons of TNT. It is equal to $4{,}18 \cdot 10^{24}$-$6{,}27 \cdot 10^{24}$ ergs, since — according to Imbo ([16]) — 1 megaton corresponds to $4{,}18 \cdot 10^{22}$ ergs. It is very reasonable to assume that the energy of the Minoan tsunami of Santorin had a greater height and greater energy than that of the tsunami of Krakatoa and the energy of air waves was at least as high as that of the air blast of Krakatoa.

By the extrapolation of the data of Iida (14) and taking into account the average values, I obtained the following results as regard the energy of tsunamis of different maximal height on the coast:

Table I

Tsunami-height metres	Tsunami-magnitude	Tsunami-energy (E_{ts}) erg
30	4,64	$1{,}528 \cdot 10^{24}$
60	5,66	$6{,}252 \cdot 10^{24}$
90	6,23	$1{,}374 \cdot 10^{25}$
120	6,65	$2{,}455 \cdot 10^{25}$
150	7,00	$3{,}981 \cdot 10^{25}$
180	7,22	$5{,}395 \cdot 10^{25}$
210	7,45	$7{,}413 \cdot 10^{25}$

Iida's formula is as follows:

$$\log E_{ts} = 21{,}4 + 0{,}6\, m \qquad [1]$$

where m is the so-called tsunami-magnitude.

It is generally accepted that as a consequence of certain volcanic eruptions large calderas may formed due to the emptying process of the magma-chamber under the volcano (17). Such phenomenon occurred in the case of Mount Mazania (Oregon), too.

Owing to such a process mighty energies are releasing in different forms. One of these energies is the total collapse energy, E_c, which can be computed by the following way:

$$E_c = Mgh\,. \qquad [2]$$

In expr. [2] M is the total mass collapsed, g the acceleration due to gravity and h the total way of the movement of the mass M in the vertical direction.

If the volcano — the collapse of which is under consideration — is situated on the open sea or ocean (e.g. Krakatoa, Santorin), it may occur that the caldera will fill up with water and as a consequence of the collapse-phenomenon and sudden changes in the topography of the sea — ocean — bottom, great waves, that is tsunamis originated from the proximity of the volcanic island. According to Schuiling and Vink (18) *the total collapse energy is used for earthquakes, tsunamis and* *for other geophysical phenomena.* On this basis we can introduce the notion of *free tectonic energy:*

$$E_{tec} = E_c - E_{ts} \qquad [3]$$

where E_{ts} is the energy of tsunami.

Let us calculate the value of free tectonic energy in case of Santorin Minoan eruption, using different values for the depth of magma-chamber and for the height of the tsunami. We used the following suppositions:

a) — total energy of water, filling the basin, bordered by the walls of the caldera: $0{,}2 \cdot 10^{25}$ ergs [18], is indicated with E_w;

b) — the total way of collapse in the vertical sense is

$$H = h + 1 \text{ km}, \qquad [4]$$

where h is the depth of the roof of magma-chamber under the sea level and H is the depth of the final magma-level inside the magma-chamber (at the moment of the beginning of the collapse), measured from the sea level (the chosen value of 1 km is a rather arbitrary one, of course);

c) — acceleration of gravity g roughly is 10^3 cm sec^{-2};

d) — the mass of the subvolcanic column is M, its density is 2,8 g cm^{-3};

e) — the mass of the collapsed material, including the preexisted volcanic mount is M_1, its density is 2,5 g cm^{-3}, its total volume is 72 km^3 and thus

$$M_1 = M + 1{,}8 \cdot 10^{17}\, g\,; \qquad [5]$$

and — lastly — the base of the preexisted volcanic mount had an area of $S = 70$ km^2. In these cases we obtain the following values:

Table II

h km	H km	M_1 10^{17} g	$E_c = (M_1 g H) + E_w$ 10^{25} ergs
1	2	3,060	6,32
2	3	4,020	12,26
3	4	6,980	28,12
4	5	8,970	45,05
5	6	10,930	65,78
10	11	20,700	227,90
15	16	31,200	499,40
20	21	40,200	844,40

Combining these data and the data, presented in Table I, furthermore taking into account expr. [3], we received the following values for the free tectonic energy:

Table III

h km	height of tsunami in metres						
	30	60	90	120	150	180	210
	free tectonic energy in 10^{25} ergs						
1	6,167	5,695	4,946	3,865	2,339	0,925	< 0
2	12,107	11,635	10,886	9,805	8,279	6,865	4,847
3	27,967	27,495	26,746	25,665	24,139	22,725	20,707
4	44,897	44,425	43,676	42,595	41,069	39,655	37,637
5	65,627	65,155	64,406	63,325	61,799	60,385	58,367
10	227,747	227,275	226,526	225,445	223,919	222,505	220,487
15	499,247	498,775	498,026	496,945	495,419	494,005	491,987
20	844,247	843,775	843,026	841,945	840,419	839,005	836,987

Very similar values may be obtained if $S = 80$ km², instead of 70. To calculate these values — however — is not necessary, since the data presented in Table III show clearly that, beginning from a certain value of h, the free tectonic energies are almost the same than the E_c, that is only a small per cent of E_c is used for tsunami.

These energies, expressed in Table III, are enormous ones. For comparison we can refer to the fact that the total seismic energy, released on the whole surface of the Earth between January 1, 1896 and the end of May, 1962 was somewhat smaller than $60 \cdot 10^{25}$ ergs (19).

What had happened with the free tectonic energy? It is a problem of capital importance.

The present author is convinced that, at least a part of this free tectonic energy, had to released as earthquakes, more exactly: in the form of *a long series of rather strong earthquakes*. A similar case had been experienced during and after the collapse of Fernandina caldera of the Galapagos volcanic group in 1968 (20) where many shocks had been occurred and some of them reached the magnitude 5,0 (Richter). It is very difficult to imagine a mighty collapse-phenomenon of gigantic mass without any shake of the ground. However it is probable that only a relatively small per cent of free tectonic energy was used for generating such a sequence of shocks. I may suggest that *the remaining part of free tectonic energy was used to cause certain changes in the level of the bottom of the Aegean-sea around the volcano Santorin.* Sorry, at present — that is about 3400 years after the event, — we are not able to measure the dimensions of the crustal deformations, happened as a direct consequence of the collapse-phenomenon. However if the changes in the sea-bottom topography were high enough, both in the horizontal and vertical direction, then the energy, necessary to produce them might have been in the order of 10^{25}-10^{26} ergs or perhaps 10^{27} ergs, that is in the order of the free tectonic energy.

As Prof. Minakami of Japan had expressed on the occasion of the congress, *the tsunamis are due to sudden topographical changes on the sea-bottom.* These topographical changes (crustal deformations) are the direct consequences of strong earthquakes, as it occurred — for instance — in case of the great Tokyo-shock on the 1st, September, 1923. But according to the considerations of the present author, discussed above, *some kind of crustal deformations may be the consequence of caldera-making collapse-process, too.* It is now quite clear and evident that *such type of crustal deformations may also cause tsunamis.* Therefore Iida's formula (14), that is expr. [1], *can be used in case of tsunamis of volcanic collapse-origin and not only in case of tsunamis of earthquake-origin.* Accordingly to use the respective formula in the calculation of the energy of Santorini Minoan tsunami is quite rightful — *quod erat demonstrandum.*

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