Volcanophysical Investigations on the Energetics of the Minoan Eruption of Volcano Santorin

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Introduction

About 3400 years ago a tremendous volcanic explosion occurred in the Aegean sea. The volcano Santorin erupted and a gigantic caldera formed during or after the explosion. According to GALANOPOULOS (1960), the volume of the caldera is some four times greater than that of the Krakatoa caldera which is estimated to be about 18 km^3 by various authors. Thus the volume of Santorin caldera may be regarded as 72 km^3.

This value is similar to the volume of destroyed rocks in the case of an other gigantic ancient volcanic eruption, namely the explosion of Mount Mazama (Crater Lake, Oregon), during which about 71 km^3 of ejecta — namely volcanic bombs and fine dust — were erupted.

Accepting the value of 72 km^3, as to Santorin case we can make some estimations concerning the energetics of the respective so-called Minoan eruption, which can be considered as second in the range of volcanic explosions of the human history (at the first place it is to be placed the Tambora eruption of 1815).

Because the useful data of Santorin are few and rather uncertain, calculations are to be made on the base of different hypotheses.

Magnitude and Energy of Eruption

Supposition 1. — The total volume of destroyed material was

$$V_1 = 72 \times 10^{15} \text{ cm}^3 \qquad [1]$$

and the average density of the respective rocks was

$$\rho = 2.8 \text{ g cm}^{-3}. \qquad [2]$$

The empirical formula (HÉDERVÁRI, 1963) giving the relationship between the eruption-magnitude M_e of a volcanic eruption of type *B* (that is, when erupted material is formed chiefly of solid fragments) and the *V* volume of ejecta is as follows:

$$M_e = \frac{\log V + 4.95}{1.59}. \qquad [3]$$

In expr. [3] *V* is given in cubic metres [1].
Substituting the numerical value of *V* into expr. [3], we get:

$$M_e^{(1)} = 9.94. \qquad [5]$$

The relationship between eruption magnitude and released thermal energy is the same as in the case of seismical magnitude and energy:

$$\log E_s = 11.8 + 1.5\, M_s \qquad [6]$$

and

$$\log E_{th} = 11.8 + 1.5\, M_e, \qquad [7]$$

where E_s is the seismical energy, M_s is the earthquake magnitude and E_{th} is the thermal energy released in the case of a volcanic eruption, the eruption magnitude of which is M_e.

From expr. [7]:

$$E_{th}^{(1)} = 5.13 \times 10^{26} \text{ erg}. \qquad [8]$$

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(1) For type *A* eruption, (it is meant the case where the erupted material is chiefly lava); in this case the formula is as follows:

$$M_e = \frac{\log V + 6.08}{1.67}. \qquad [4]$$

Let the relation between thermal energy E_{th} and kinetic energy be

$$E_{kin}^{(1.1)} = \frac{1}{100} E_{th}. \qquad [9]$$

Thus

$$E_{kin}^{(1.1)} = 5.13 \times 10^{24} \text{ erg}. \qquad [10]$$

On the other hand E_{kin} may be written in this form:

$$E_{kin} = 0.5\ m^{(1)}\ v_o^2, \qquad [11]$$

where $m^{(1)}$ is the total mass of the volcanic bombs, the volume and density of which are V_1 and ρ, respectively; and v_o being the initial speed of volcanic bombs (neglecting the drag of the atmosphere). The numerical values of v_o valid for different relations between E_{kin} and E_{th} can be found in Table 1.

TABLE 1.

Supposition	E_{kin}	v_o m sec^{-1}	No. of expression
1.1	$\frac{1}{100} E_{th}(1)$	71.3	[12]
1.2	$\frac{2}{100} E_{th}(1)$	101.6	[13]
1.3	$\frac{3}{100} E_{th}(1)$	123.6	[14]
1.4	$\frac{4}{100} E_{th}(1)$	142.7	[15]
1.5	$\frac{5}{100} E_{th}(1)$	159.6	[16]
1.6	$\frac{10}{100} E_{th}(1)$	225.6	[17]
1.7	$\frac{20}{100} E_{th}(1)$	318.9	[18]
1.8	$\frac{30}{100} E_{th}(1)$	390.7	[19]
1.9	$\frac{40}{100} E_{th}(1)$	451.2	[20]
1.10	$\frac{50}{100} E_{th}(1)$	504.4	[21]
1.11	$\frac{75}{100} E_{th}(1)$	617.9	[22]
1.12	$\frac{99}{100} E_{th}(1)$	709.8	[23]

Supposition 2. — Let us suppose now that the total volume of destroyed material was

$$V_2 = 7.2 \times 10^{15} \text{ cm}^3 , \qquad [24]$$

and the cavity of the caldera was formed not only by the effective explosion but a certain (and sudden) collapse of the wall of the conduit immediately under the crater had also an important role in the formation of the caldera. Thus the total volume of the caldera may be written in this form:

$$Q = V_2 + q_1 , \qquad [25]$$

where V_2 is the total volume of volcanic bombs while the volume of cavity (which cavity was formed directly by the collapse process)

$$q_1 = 64.8 \times 10^{15} \text{ cm}^3 . \qquad [26]$$

In this case

$$M_e^{(2)} = 9.31 \qquad [27]$$

and

$$E_{th}^{(2)} = 5.82 \times 10^{25} \text{ erg}. \qquad [28]$$

Now

$$E_{kin} = 0.5 \ m^{(2)} \ v_o^2 , \qquad [29]$$

where $m^{(2)}$ is the total mass of the volcanic bombs, the volume and density of which are V_2 and ρ, respectively.

The numerical values of v_o valid for the different cases are given in Table 2.

TABLE 2.

Supposition	E_{kin}	v_o m sec^{-1}	No. of expression
2.1	$\frac{1}{100} E_{th}(2)$	76.0	[30]
2.2	$\frac{10}{100} E_{th}(2)$	240.3	[31]
2.3	$\frac{50}{100} E_{th}(2)$	537.2	[32]
2.4	$\frac{75}{100} E_{th}(2)$	658.0	[33]

Supposition 3. — Let us suppose finally that the total volume of destroyed material was only

$$V_3 = 0.72 \times 10^{15} \text{ cm}^3 \qquad [34]$$

and the greatest part of the cavity of caldera was formed chiefly by the collapse of the magma chamber. Thus the total volume of the caldera may be written in the following form:

$$Q = V_3 + q_2 , \qquad [35]$$

where V_3 is the total volume of volcanic bombs and q_2 the volume of cavity formed directly by the collapse-process.

In this case

$$M_e^{(3)} = 8.68 \qquad [36]$$

and

$$E_{th}^{(3)} = 6.61 \times 10^{24} \text{ erg.} \qquad [37]$$

Now

$$E_{kin} = 0.5 \; m^{(3)} \; v_o^2 , \qquad [38]$$

where $m^{(3)}$ is the total mass of the volcanic bombs, the volume and density of which are V_3 and ρ, respectively.

The results of calculation concerning the value of v_o in the different cases can be found in Table 3.

TABLE 3.

Supposition	E_{kin}	v_o m sec^{-1}	No. of expression
3.1	$\frac{1}{100} E_{th}(3)$	81.1	[39]
3.2	$\frac{10}{100} E_{th}(3)$	256.0	[40]
3.3	$\frac{50}{100} E_{th}(3)$	572.6	[41]
3.4	$\frac{75}{100} E_{th}(3)$	701.3	[42]

According to GALANOPOULOS (1961) the intensity of the earthquake occurred during or immediately after the great eruption of Santorin might have reached 12° on the Mercalli-Sieberg scale. In this case — supposing the hypocenter of the greatest shock to be shallow ($0 < h \leqslant 70$ km) — the magnitude of the earthquake was at least 8,0 or perhaps over it.

Supposing a hypocenter-depth of 20 km, the relation among the different quantities can be found in Table 4.

TABLE 4.

Degree of intensity of shock	Magnitude (M)	Energy, 10^{23} erg	Radius of perceptibility, km	Acceleration, mm sec^{-2}
10	7.5	1.12	500	1.000 - 2.500
11	8.0	6.31	600	2.500 - 5.000
12	8.0 —	6.31 —	600 —	2.500 -
	8.5	35.49	> 900	- 10.000

At any rate $M \geqslant 8.0$ is an unusually great value for a shock of volcanic origin. However it is not impossible. For instance: the strongest shocks, occurred on the occasion of the eruption of Etna in March, 1669, had an intensity of at least 9° on the Mercalli-Sieberg scale. The equivalent seismical magnitude of these shocks might have been about 7.0 or somewhat over it. The volcanic earthquake occurred in the time of the eruption of Hekla in Iceland had an energy of 1.5×10^{22} erg (SIEBERG), that is its magnitude might have been about 6.9. The energy of the volcanic earthquake after the eruption of Sakurajima (Japan) in 1914 was 5.5×10^{22} erg (SIEBERG), that is the magnitude reached 7.3. According to RICHTER (1958): « On June 7, 1912, after the great eruption of Katmai had started, an earthquake of magnitude 6.4 occurred off the adjacent Alaskan coast; another of magnitude 7.0 followed on June 10 ».

Accepting the value of

$$M_s = 8.0 \qquad [43]$$

for the magnitude of the *volcanic* earthquake occurred on the occasion of the Minoan eruption of Santorin, on the bases of expression

$$\log E_s = 11.8 + 1.5\, M_s \qquad [44]$$

we get

$$E_s = 6.31 \times 10^{23} \text{ erg.} \qquad [45]$$

According to GORSHKOV's investigation concerning the extraordinary eruption of volcano Bezymianny of Kamchatka, in March, 1956 (GORSHKOV, 1959),

$$E_{th} > 10^3 E_s . \qquad [46]$$

In the case of the eruption of Sakurajima in 1914 the relation was

$$E_{th} \backsimeq 10^3 E_s , \qquad [47]$$

and in the case of Katmai's explosion

$$E_{th} \backsimeq 10^4 E_s \qquad [48]$$

and/or

$$E_{th} \backsimeq 10^5 E_s . \qquad [49]$$

A similar result had been experienced by YOKOYAMA (1956, 1957) for the sequence of eruptions of the Japanese volcano Mihara-Yama in 1950-1951. According to YOKOYAMA

$$E_{th} > 10^3 E_s . \qquad [50]$$

By considering the above relationship (exprs. [46], [47], [48], [49], and [50]) *in the case of Santorin the possible greatest eruption magnitude seems to be the most probable one.* Namely, in the case of

$$M_s \geqq 8.0, \qquad [51]$$

$$E_s \geqq 6.31 \times 10^{23} \text{ erg,} \qquad [52]$$

and since

$$E_{th} \gtrapprox 10^3 E_s , \qquad [53]$$

therefore

$$E_{th} \gtrapprox 6.31 \cdot 10^{26} \text{ erg.} \qquad [54]$$

Thus the thermal energy E_{th}, calculated on the basis of the probable magnitude of the volcanic earthquake, would be very likely greater than the thermal energy $E_{th}^{(1)}$, given in [8] and calculated by considering

$$M_e^{(max)} = 9.94. \qquad [55]$$

This result suggests the validity of the $M_e^{(max)}$ against the other possible eruption magnitudes, namely $M_e^{(2)} = 9.31$, see expr. [27]; and $M_e^{(3)} = 8.68$, see expr. [36].

In other words, the result shows that the volume of the total destroyed material (that is the total volume of volcanic bombs and fine dust) was really about 72×10^{15} cm^3. Therefore *the Supposition 1 seems to be the most probable one.*

Let us now suppose that the intensity of the volcanic earthquake was slightly smaller than 12° on Mercalli-Sieberg scale. If the intensity was 10° or 11° respectively, then the magnitude of the earthquake was 7.5 or 8.0 as a maximum. In these cases — as it can be seen from Table 4 — the energy of the shock was

$$1.12 \times 10^{23} \text{ erg} \leqq E_s \leqq 6.31 \times 10^{23} \text{ erg}. \qquad [56]$$

Taking into account expr. [53], the thermal energy was 1.12×10^{26} erg minimum, while maximally it might have been about 6.31×10^{26} erg. Both values are also very near to the acceptable, real value of 5.13×10^{26} erg, corresponding the eruption magnitude 9.94.

According to SAKUMA and NAGATA (1957): « The seismic energy of an explosion-earthquake is 10^{-2} to 10^{-4} of the kinetic energy of the ejecta, as far as the activity of explosive type is concerned ».

The present estimations and result, respectively, are in congruence with this establishment. Namely (see later, in exps. [68] and [69], respectively)

$$E_{kin} = 3.76 \times 10^{26} \text{ erg} \qquad [57]$$

and — in the case of

$$M_s \backsimeq 8.0, \text{ —} \qquad [58]$$

$$E_s = 6.31 \times 10^{23} \text{ erg}, \qquad [59]$$

therefore

$$\frac{E_{kin}}{E_s} \backsimeq 6 \times 10^2. \qquad [60]$$

We can take some comparison between Santorin and other volcanoes. The explosion of Santorin was by all means *greater* than that of Bezymianny and without doubt was *smaller* than that of volcano Tambora of Indonesia in 1815. According to GORSHKOV (1959) the volume of destroyed material in the case of Bezymianny of Kamchatka in 1956 was only about 2.8×10^{15} cm^3, while — according to

VERBEEK — in the case of Tambora it was about 150×10^{15} cm^3.

Since the magnitude of Santorin eruption is between the magnitude of Bezymianny and Tambora, therefore we may assume that the initial speed of volcanic bombs in the case of Bezymianny was *smaller* and in the case of Tambora was *greater* than in the Santorin case:

$$v_o^{(\text{Bezymianny})} < v_o^{(\text{Santorin})} < v_o^{(\text{Tambora})}. \qquad [61]$$

According to GORSHKOV's estimation

$$v_o^{(\text{Bezymianny})} \backsimeq 600 \text{ m sec}^{-1}. \qquad [62]$$

On the other hand the volcanic bombs during the Tambora explosion spread over a circular area, the radius of which was

$$r \backsimeq 40 \text{ km} \qquad [63]$$

(YOKOYAMA). Since the initial speed of bombs:

$$v_o = \sqrt{rg}, \qquad [64]$$

where r is the radius and g is the acceleration due to gravity, — in the case of Tambora we get:

$$v_o^{(\text{Tambora})} \backsimeq 624 \text{ m sec}^{-1}. \qquad [65]$$

Let us regard now that the value valid for the case of Santorin, is

$$v_o^{(\text{Santorin})} = \frac{v_o^{(\text{Bezymianny})} + v_o^{(\text{Tambora})}}{2} = 612 \text{ m sec}^{-1}. \qquad [66]$$

Hence

$$r^{(\text{Santorin})} \backsimeq 38 \text{ km}. \qquad [67]$$

If expr. [66] holds, then

$$E_{kin} = 73.4 \text{ per cent of } E_{th}^{(1)}, \qquad [68]$$

that is

$$E_{kin} = \frac{73.4}{100} E_{th}^{(1)} = 3.76 \times 10^{26} \text{ erg}. \qquad [69]$$

The value given in expr. [68] is close to the value used in *Supposition 1. 11.* Accordingly the Santorin eruption was a rather particular one, in which the kinetic energy had a very great role against the thermal one. Generally $E_{kin} = 1$, 2 or 3 per cent of E_{th}, although there are exceptional cases, too. For instant, according to YOKOYAMA, in the case of Krakatoa

$$E_{kin}^{(\mathrm{Krakatoa})} \backsim \frac{25}{100} E_{th}^{(\mathrm{Krakatoa})}. \quad [70]$$

The eruption of Santorin reminds us in more respect to that of the Krakatoa explosion.

Concerning the intensity of the Santorin eruption in accordance with the TSUYA-scale, we can state that the intensity reached VIII°. The corresponding eruption magnitude in the case of A-type is 9.95 $\pm$ 0.30, and in the case of B-type is 9.6875 $\pm$ 0.3125 (HÉDERVÁRI, 1963). It may be noted that according to a new calculation of volcanic energy, made by G. IMBÒ (1965) the intensity of VIII° on Tsuya's scale corresponds to an eruptive magnitude of 9.0 $\pm$ 0.3. This disagreement is justified by considering that the eruption magnitude used by the present author is based on the thermal energy while the eruptive magnitude used by IMBÒ is based on the mechanical energy.

Energy of Tsunami and Air-wave

We can estimate the energy and magnitude of the tsunami, too, occurred immediately after the extraordinary explosion of Santorin.

According to the investigations of IIDA (1958):

$$m^{*} = 2.61\ M_{s} - 18.44. \quad [71]$$

In expr. [71], m^{*} is the so-called tsunami-magnitude and M_s the magnitude of the (sea) quake. We supposed that the tsunami, which followed the great explosion of Santorin, originated by the simultaneous earthquake (actually seaquake).

If

$$M_{s} = 8.0 \quad [72]$$

then

$$m^{*} = 2.44 \quad [73]$$

and the energy of the tsunami may be written in this form (IIDA):

$$\log E_{ts} = 21.4 + 0.6\, m^*, \qquad [74]$$

hence

$$E_{ts} = 7.31 \times 10^{22} \text{ erg.} \qquad [75]$$

The height of water-waves over the open sea in the case of $m^* = 2.44$ was about 6-8 metres.

Also using IIDA's formula, the L length of the front-line of the tsunami can be calculated by expr. [76]:

$$\log L = 0.5\, M_s - 1.8, \qquad [76]$$

hence

$$L \backsimeq 160 \text{ km.} \qquad [77]$$

But if

$$M_s > 8.0, \qquad [78]$$

then evidently

$$L > 160 \text{ km,} \qquad [79]$$

that is the tsunami was great enough to sweep along the Northern coast of island Creta, as GALANOPOULOS has suggested. Since the caldera of Santorin is open towards the Southwest, it is very probable that the tsunami was the strongest in the same direction (supposing that the epicenter was under the central volcanic peak of Santorin) and therefore the damage was the greatest firstly on Northwestern Creta.

We can also calculate the speed of the respective tsunami. The speed of a seismical sea-wave may be written in this form:

$$v_{ts} = \sqrt{H g}. \qquad [80]$$

Here H is the average depth of the sea (or ocean) and g is the acceleration due to gravity.

Let us suppose that the average depth of the sea between the volcano Santorin and Creta is

$$H \backsimeq 1{,}500 \text{ metres,} \qquad [81]$$

then, in accordance with expr. [80], the speed roughly was:

$$v_{ts} \backsimeq 120 \text{ km hour}^{-1}, \qquad [82]$$

which is a rather low value comparing with the speed of other tsunamis, occurred in the Pacific Ocean.

Concerning the energy of air-waves after the Santorin eruption, we also may refer to GORSHKOV's estimation, who has suggested that

$$E_{kin} \backsimeq 10\ E_{aw}, \qquad [83]$$

where E_{aw} is the energy of air-waves.

Thus, in the case of Santorin:

$$E_{aw} \backsimeq 4 \times 10^{25}\ \text{erg}. \qquad [84]$$

This gigantic energy is about equal with the rotational kinetic energy of a large North-Atlantic depression or about 1,000-10,000 times greater than the total energy of a *tornado*! Namely, according to LANE (1966) the approximate kinetic energy of rotation of a tornado with a diameter of about 100-110 metres — a small one — is about 10^{18} erg per second. The total life-time of a tornado (TALMAN, 1938) is about an hour. Thus the order of magnitude of the total energy of a smaller tornado may be about 4×10^{21} erg while that of a very strong one may be about 10-times greater.

Concerning this point we may refer to the very interesting and remarkable fact that after the terrible explosion of Tambora in 1815 tornadoes originated which were the strongest ever observed (LANE, 1966). « They snatched up men, horses, cattle, and anything moveable. The largest trees were torn out of the ground by the roots and whirled into the air. For days during the eruptions the surrounding seas were littered with trees and branches » — wrote LANE, referring to C. E. WURTZBURG and J. T. ROSS.

Concerning the power of *normal* tornadoes, we may refer also to TALMAN and LANE, respectively. TALMAN wrote that a horse was transferred by a normal tornado over a distance of about 3.6 km and a roof was transferred by a tornado over a distance of 19 km. LANE said that tornadoes have been known to carry large iron bridges from their foundations. For example, « the extremely violent tornado which struck Irving, Kansas, on May 30, 1879, lifted a large iron bridge from its piers and twisted it into an iron scap heap... ». And: « An 800-pound ice chest was transported over three miles. The spire of a church, complete with weathercock, was carried 15 miles through the air. A wooden house was blown two miles... » — etc.

These fantastic facts show clearly the startlingly gigantic power of a *normal* tornado. But the tornado which might have been occurred at the time of Santorin explosion were not a normal one! Taking into consideration the energy of air-waves we must suppose that the respective tornado was en *extraordinarily strong one*, simliar to the tornadoes occurred at the time of Tambora eruption.

According to GORSHKOV, the energy of air-waves after the eruption of volcano Bezymianny was about 3×10^{22} erg, while — according to YAMAMOTO — the energy of air-waves due to the explosion of the greatest hydrogen-bomb was « only » about 1.4×10^{21} erg.

We shall return to the possible effect of the extremely strong tornado — occurred during or immediately after the explosion of volcano Santorin — at the end of the present paper.

Point of Time of Santorin Minoan Eruption

GALANOPOULOS (1960) stated, that « A really great tsunami may have started in the Aegean Sea after the tremendous explosion of Santorin volcano, which occurred 3,370 ± 100 years ago ». On the other hand, Professor MARINATOS stated that all the Minoan cities and localities on the North and East coast of Creta were swept clean by the tsunami. In accordance with the results of archaelogical researches, made by MARINATOS, the great catastrophe might have occurred about 3,460-3,470 years ago. Lastly, according to radio-carbon data, the events might have been occurred 3,410-3,420 years ago.

Pressure and Temperature of Gases (2)

Concerning the problem of the Minoan eruption of volcano Santorin, Professor GALANOPOULOS had the kindness to draw the attention of the author to the fact, that according to Professor NICOLAS PLATON (1966) large pieces of volcanic lava have been found in the palace of Zakro and piles of pumice stones on other parts of the coast. (Private communication, 1967).

Since Zakro is in a distance of about 160 km from Santorin, calculating by the formula

$$v_0 = \sqrt{g r} \qquad [85]$$

(2) The calculations in this chapter are the common work of the author P. HÉDERVÁRI and Mr. ISTVÁN PADOS, physicist, scientific collaborator of « Gamma Geofizika », Budapest.

we should get for the initial speed of the volcanic bombs a very great value, about 1,270 m sec^{-1}. (In expr. [85] v_o is the initial speed, g is the acceleration due to gravity and r is the distance, in this case $r = 160$ km).

The pieces of volcanic lava found at Zakro are too heavy to have been transferred by the sea-waves. Therefore we must make a choice between two possibilities.

a) The bombs were transferred from Santorin to Zakro directly by the power of the great explosion; or

b) they were transferred by an other natural phenomena.

We shall prove that case *a*) leads to impossibilities.

First of all let us take that the value $v_o = 1{,}270$ m sec^{-1} means an average one for the initial speed of volcanic bombs. (It is noteworthy that the real value had to be somewhat greater since in the case of such a great speed and distance the drag of the atsmosphere is rather considerable. The effective orbit of the bombs isn't parabolic but ballistic; the bombs move as ballistic missiles. Therefore the initial speed of the bombs had to be greater with at least 10 per cent or more).

Disregarding from the problem of the atmospheric drag, the value of v_o as an average one seems to be extraordinarily high. Namely, in this case E_{kin} would be about 1.63×10^{27} erg, which is greater than E_{th}. It seems to be quite strange and impossible that the kinetical energy of any kind of volcanic eruption would be greater than the thermal one of the same eruption. On the other hand, as it was mentioned earlier, the magnitude of Santorin's respective eruption — calculated on the value of $V = 72$ cubic kilometres for the total volume of destroyed material — must be between the magnitude of the eruption of Bezymianny and Tambora, respectively, since the volume of destroyed material in Bezymianny's case was only about 2,8 cubic kilometres while in the case of Tambora it was about 150 cubic kilometres. Therefore it seems to be logical to suppose that the average initial speed of volcanic bombs in the case of Bezymianny was smaller and in the case of Tambora eruption was greater than in the Santorin's case.

Now, we are setting out from the empirical fact that on the occasion of the eruption of a volcano the pressure-energy — accumulated in matter — transformed into the potential and kinetic energy of the volcanic bombs. In this case — on the base of the law of the conservation of energy — we can write:

$$E_{pr} \Rightarrow E_{pot} + E_{kin} = \text{constant}. \qquad [86]$$

Here the mark $\Rightarrow$ means the transformation of pressure-energy E_{pr} into the sum of potential energy E_{pot} and kinetic energy E_{kin}. If the initial speed of the bombs is v_o and the drug of the atmosphere is neglected, furthermore α means the angle between the tangent of the bombs' orbit and the horizontal line in the explosion-point at the moment of the explosion, then

$$v_y = v_o \sin \alpha \qquad [87]$$

and

$$v_x = v_o \cos \alpha. \qquad [88]$$

Let H be the height which is reached by the bombs in the case of whichever angle α. Then the following, well-known formula is valid:

$$H = \frac{v_o^2 \sin^2 \alpha}{2 g} \qquad [89]$$

were g is the gravitational acceleration.

Those bombs can reach the maximal distance from the explosion-point, for which

$$\alpha = 45°. \qquad [90]$$

In this case the maximal height of the orbit of the bombs is

$$v_y = v_o \frac{\sqrt{2}}{2} \qquad [91]$$

and the maximal distance from the point of explosion is

$$v_x = v_o \frac{\sqrt{2}}{2}. \qquad [92]$$

On the base of expr. [89]:

$$H_{45°} = \frac{v_o^2}{4 g}. \qquad [93]$$

The potential energy of bombs (taking into account expr. [93], if m means the total mass of the bombs, reached the height H), will be as follows:

$$E_{pot} = m\,g\,H_{45^\circ} = \frac{1}{4}\,m\,v_o^2. \qquad [94]$$

Taking into consideration expr. [92], the kinetic energy of the bombs is:

$$E_{kin} = \frac{1}{2}\,m\,v_x^2 = \frac{1}{4}\,m\,v_o^2. \qquad [95]$$

Let the total volume of the bombs be V and the pressure P_t valid for a temperature t, then we may write from expr. [86]:

$$\frac{1}{2}\,m\,v_o^2 = P_t\,V = P_t\,\frac{m}{\rho} \qquad [96]$$

where ρ is the density of the material of the volcanic bombs. From expr. [96] we get:

$$v_o = \sqrt{2\,\frac{P_t}{\rho}}\,. \qquad [97]$$

Thus we can calculate the average speed of the bombs if we knew the pressure P_t. The pressure as the function of temperature roughly is:

$$P_t \backsim \left(\frac{t}{100}\right)^4. \qquad [98]$$

Expr. [98] gives us the pressure in kg cm^{-2}.

Substituting the value of P_t into expr. [97], we get

$$v_o \backsim \sqrt{\frac{2}{\rho}\left(\frac{t}{100}\right)^4}. \qquad [99]$$

We have supposed that the density of the material of bombs, ρ might have been about 2.8 g cm^{-3} in average. In this case, if $t =$ $=$ 1,000 C°:

$$v_o^{(1{,}000\,C^\circ)} = 837 \text{ m sec}^{-1} \qquad [100]$$

and if t = 800 C°, then

$$v_o^{(800\,C^\circ)} = 537 \text{ m sec}^{-1}. \qquad [101]$$

From exp. [99]:

$$v_o^2 \frac{\rho}{2} \backsim \left(\frac{t}{100}\right)^4 \text{kg cm}^{-2} = \left(\frac{t}{100}\right)^4 \times 9.81 \times 10^5 \text{ dynes cm}^{-2}, \quad [102]$$

and from here

$$t \backsim 10 \sqrt[4]{\frac{\rho\, w_o^2}{196{,}2}} \text{ C}^o. \quad [103]$$

If, in accordance with the earlier supposition, in the case of Santorin

$$v_o = 612 \text{ m sec}^{-1} \quad [104]$$

then, according to expr. [103]:

$$t_{612} = 885 \text{ C}^o. \quad [105]$$

This value is quite real and probable. As it is well-known, the temperature of the gas cloud in the case of volcanoes of Sakurajima-type is about 800-900 C°, while the temperature of the lava of the same type is at least 900 C° or over it. On the other hand the temperature of « nuées ardentes » on the occassion of Mont Pelé eruption in 1902 was about 800 C°.

Taking these facts into consideration the value of 855 C° for the gase-temperature in the Santorin's case is acceptable.

The pressure at the moment of the great explosion, calculated from expr. [98] is:

$$P_t^{(855\text{ C}^o)} = 5{,}343 \text{ kg cm}^{-2}. \quad [106]$$

This value also seems to be very reasonable since — according to GORSHKOV (1959) — the pressure in the case of Bezymianny explosion might have reached a value of 3,000 kg cm^{-2}.

Now let us take a calculation on the base of $v_o = 1{,}270$ m sec^{-1}, where v_o is the initial speed of bombs in accordance with the following suppositions:

a) The reached distance r was 160 km;

b) the angle α was 45°;

c) the atmospheric effect (drag) was neglected;

d) the force, which made fly away the bombs from the explosion-point to such a great distance was directly the eruption itself and *not* some sort of other phenomena, such as are for instance the extraordinarily powerful shock wave or series of shock waves in the air and/or a tornado, occurred immediately after the great eruption.

In this case:

$$t_{1270} = 1230 \text{ C}^{\circ} \qquad [107]$$

and

$$P_t^{(1230\text{ C}^{\circ})} = 22{,}888 \text{ kg cm}^{-2}. \qquad [108]$$

Both values seem to be *too high*, especially the pressure.

Conclusion

Regarding the results, discussed in the previous section, we can state that the value of $v_0 = 1270$ m sec^{-1}, valid for a distance of $r = 160$ km is *improbable*, hence it leads to irreally great values for both the temperature and pressure. Really, if we took into account the drag of the atmosphere, $v_0^{(\text{real})}$ is still greater than 1270 m sec^{-1}. Consequently in this case the temperature and pressure would also be greater than 1230 C° and 22888 kg cm^{-2}, respectively.

Under these circumstances how can we interpret the empirical fact, discovered by Professor PLATON? What might have been the cause that *some* volcanic fragments reached a distance of about 160 km from Santorin?

The present author supposes that the cause might have been the shock wave or a series of shock waves with an energy of about 4×10^{25} erg (see in expr. [84]), *and/or* an abnormally powerful tornado, originated simultaneously with the gigantic explosion of Santorin or immediately after the eruption.

Final Values

In the following table the accepted values of the Minoan eruption of volcano Santorin are given.

TABLE 5.

Eruption magnitude	M_e	9.94
Thermal energy	E_{th}	5.13×10^{26} erg
Kinetic energy	E_{kin}	73.4 per cent of E_{th} = = 3.76×10^{26} erg
Destroyed material = volume of volcanic bombs (including fine dust, too)	V	72×10^{15} cm^3
Initial speed of bombs (neglecting the drag of atmosphere)	v_o	612 m sec^{-1}
Intensity of eruption on scale of TSUYA	J	VIII°
Maximal intensity of the strongest volcanic shock on scale of MERCALLI and SIEBERG	I_o	12°
Magnitude of the strongest volcanic shock	M_s	$\geqslant$ 8.0
Magnitude of tsunami	m^*	$\geqslant$ 2.44
Energy of tsunami	E_{ts}	$\geqslant 7.31 \times 10^{22}$ erg
Front-line of tsunami	L	$\geqslant$ 160 km
Speed of tsunami	v_{ts}	$\cong$ 120 km hour^{-1}
Height of tsunami-wave	h	6 - 8 metres
Energy of air-waves	E_{aw}	$\cong 4 \times 10^{25}$ erg
Pressure of gases	P_t(855 C°)	$\cong$ 5,343 kg cm^{-2}
Temperature of gases	t_{612}	$\cong$ 855 C°
Estimated energy of the possible tornado (where e_{tor} is the total energy of a very small tornado)	E_{tor}	$e_{tor} = 4 \times 10^{21}$ erg $< E_{tor} < 4 \times 10^{25}$ erg $= E_{aw}$
Energy of the lifting lava	E^*	unknown, since both the exact depth of magma chamber and the mass of the lifting lava are unknown

Thus, the total energy of the Minoan eruption of Santorin may be written in this form:

$$E_{total} = E_{th} + E_{kin} + E_s + E_{ts} + E_{aw} + E_{tor} \cong 10^{27} \text{ erg} + \\ + E^* + E_x \qquad [109]$$

where E_s is the energy of the volcanic earthquake and E_x means unknown factors.

Comparison with Other Phenomena

Finally — for the sake of comparison — we show some data concerning the energetics of volcanoes and other phenomena (Table 6 and Table 7).

TABLE 6.

Phenomena	Energy, erg	Author
Volcanic earthquake after the eruption of volcano Hekla (Iceland), 1912	1.5×10^{22}	SIEBERG
Volcanic earthquake after the eruption of volcano Sakurajima (Japan), 1914	5.5×10^{22}	SIEBERG
Earthquake in Messina, 1909	5.7×10^{22}	GUTENBERG, RICHTER (1954)
Tsunami after one of the strongest shock of the great Chilean earthquake-sequence in 1960	1.6×10^{23}	IIDA
Earthquake in San Francisco, 1906	1.8×10^{24}	GUTENBERG, RICHTER
Thermal energy, released during the formation of volcanic island Surtsey (Iceland), 1963	2.0×10^{24}	HÉDERVÁRI (1965)
Strongest shock of the great Alaskan earthquake, 1964	5.0×10^{24}	Seismological Notes, Bull. of the Seismological Soc. of America
Thermal energy of the eruption of volcano Fuji-Yama (Japan), 1707	7.1×10^{24}	YOKOYAMA (1956-57)
Thermal energy of the eruption of volcano Asama-Yama (Japan), 1783	8.8×10^{24}	MINAKAMI

TABLE 6 (*cont'd*).

Phenomena	Energy, erg	Author
Thermal energy-content of the lavatower of Mont Pelée (Martinique), 1902	$\simeq 10^{25}$	HÉDERVÁRI (1963)
Earthquakes in the Pacific Ocean: *a*) near Ecuador and Columbia, 1906 and *b*) near Marioka (Japan), 1933	1.4×10^{25}	RICHTER (1958)
Earthquake in Lissabon (Portugal), 1755 - probable the greatest shock of human history	2.0×10^{25}	GUTENBERG, RICHTER
Thermal energy of the eruption of volcano Bezymianny (Kamchatka), 1956	2.2×10^{25}	GORSHKOV (1959)
Total energy of the eruption of volcano Sakurajima (Japan), 1914	5.2×10^{25}	MATUZAWA
Thermal energy of the eruption of volcano Krakatoa (Indonesia), 1883, calculated on the base that $V = 18 \times 10^{15}$ cm^3	1.7×10^{26}	HÉDERVÁRI (1963)
Total energy of the same eruption	1.8×10^{26}	HÉDERVÁRI
Thermal energy of the eruption of volcano Katmai (Alaska), 1912	2.0×10^{26}	HÉDERVÁRI
Total seismic energy released over the Pacific area between 1904-1964	2.95×10^{26}	DUDA (1965)
Total seismic energy released on the Earth as a whole between 1904-1964 (these two data due to DUDA are valid for earthquakes between the magnitude-range of 7.0 - 8.9)	3.87×10^{26}	DUDA
Thermal energy of the eruption of volcano Coseguina (Nicaragua), 1835	4.8×10^{26}	HÉDERVÁRI
Thermal energy of the eruption of volcano Mount Mazama (Oregon) in ancient time, calculated on the supposition that $V = 71 \times 10^{15}$ cm^3	6.8×10^{26}	HÉDERVÁRI
Thermal energy of the eruption of volcano Tambora (Indonesia), 1815, calculated on the base that $V = 100 \times 10^{15}$ cm^3	8.4×10^{26}	YOKOYAMA
Thermal energy of the same eruption, calculated on the base that $V = 150 \times 10^{15}$ cm^3	1.4×10^{27}	HÉDERVÁRI
Thermal energy of the formation of Ooshima volcanic island (Japan)	2.0×10^{27}	YOKOYAMA
Thermal energy of a lunar crater's formation, if the diameter is 10 km (supposing a volcanic origin)	3.8×10^{27}	HÉDERVÁRI (1962)
Thermal energy released during the formation of the largest lunar crater (Clavius), supposing a volcanic origin	1.4×10^{30}	HÉDERVÁRI

Lastly, the initial velocity of volcanic bombs and other fragments:

TABLE 7.

Volcano	v_0 m sec^{-1}	Author
Tokachidake, Japan, 1926	80	YOKOYAMA
Kusatsu-Shiranesan, Japan, 1932	128	»
Pematang Bata, Sumatra, 1933	147	»
Azumasan, Japan, 1893	148	»
Bandaisan, Japan, 1888	170	»
Krakatoa, Indonesia, 1883	193	»
Asama-Yama, Japan, 1783	250	»
Bezymianny, Kamchatka, 1956	600	GORSHKOV
Tambora, Indonesia, 1815	624	YOKOYAMA *

* Calculated by the data of *r*, given by YOKOYAMA.

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