6. *Energetics in Active Volcanoes. 2nd Paper.*

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Summary

Energetics related to the 1950～52 activities of Volcano Mihara, Ooshima Island are analysed in Part I of this paper in a way similar to the writer's previous paper. In Part II, the study of energetics of volcanic action is extended to many volcanoes in Japan and foreign countries, the discussion being made on the basis of the results obtained by the analyses of activities of Volcano Mihara during the period from 1950 to 1954.

PART I.

Activities of Volcano Mihara, Ooshima Island during the Period 1950 ～ 1952.

Volcano Mihara, Ooshima Island commenced an eruption at the crater on July 16, 1950 after 10 years' quiescence. The eruption continued until Sept. 23, 1950 displaying progressive activities of the *Strombolian* type. Next year, from Feb. 4 to June 28, the volcano resumed its activity on a larger scale. We name these two years' activities the 1950–51 eruption, which seems to be one of the most violent eruptions in historical times ranking with the 1777–78 eruption.

As a continuation of the previous paper[1], the writer is going to summarize here all the data related to energetics of volcanic action observed on Volcano Mihara during the period from 1950 to 1952, the method of the analysis being based upon the same principle as the one in the previous analyses.

1. Energy of volcanic tremors.

In estimating the energy of volcanic tremors on Volcano Mihara during the period, the writer investigates the seismometrical records obtained by the Ooshima Weather Station which is situated at a dis-

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[1] I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **34** (1956), 185.

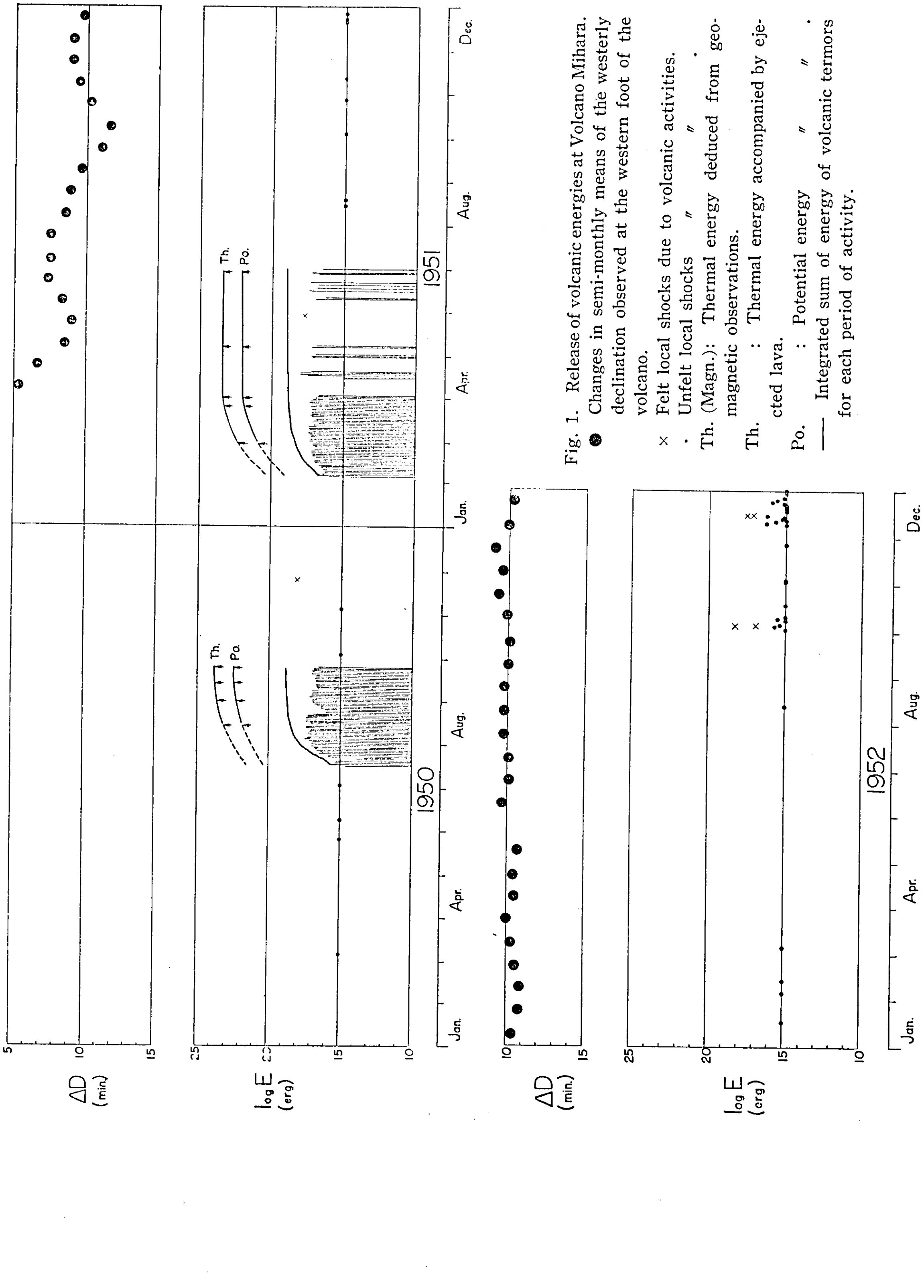
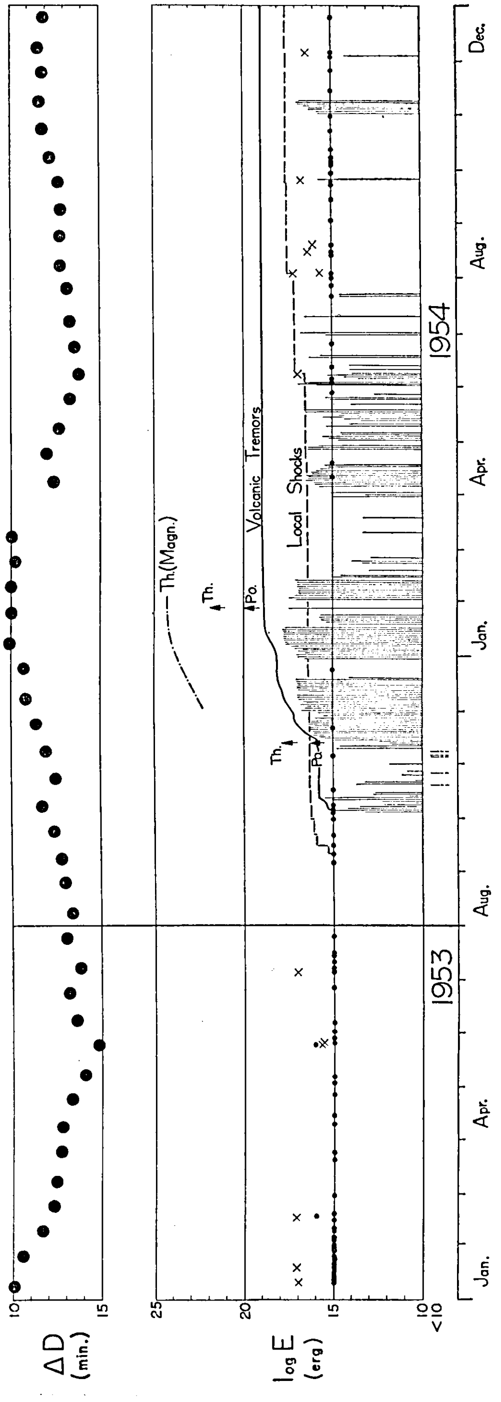


Fig. 1. Release of volcanic energies at Volcano Mihara.

- ● Changes in semi-monthly means of the westerly declination observed at the western foot of the volcano.
- × Felt local shocks due to volcanic activities.
- · Unfelt local shocks 〃 〃 .
- Th. (Magn.): Thermal energy deduced from geomagnetic observations.
- Th. : Thermal energy accompanied by ejected lava.
- Po. : Potential energy 〃 〃 .
- — Integrated sum of energy of volcanic termors for each period of activity.



tance of 4.8 *km* from the crater. Some investigations of these records had already been carried out by Y. Kizawa[2] who kindly placed his data at the writer's disposal. Kizawa has given the maximum amplitude of the three components of volcanic termors at 08 and 20 *h* every day. By K. E. Bullen's method as was adopted in the previous paper, the daily energy which is emitted as tremors is approximately given by

$$E=2.68\times 10^{10}\sum_{1}^{2} A^2 \frac{\Delta T}{\tau}(erg), \tag{1}$$

where A is the amplitude of the horizontal component measured in *micron* and τ is the period of vibration which varies from 0.6 to 0.8 *sec*. For the sake of convenience, we assume the duration time ΔT as 6 *hours*. The results thus obtained are shown by the columns for each day in Fig. 1.

2. Energy of volcanic earthquakes.

The energy of local shocks of volcanic origin is estimated from the seismometrical data obtained by the Ooshima Weather Station. The seismometers are Wiehert-type ones usually having

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[2] Y. KIZAWA, *Jour. Geogra.* (Tokyo), **60** (1951),128.

magnification 100, period 5.0 *sec.* and damping ratio 7. Monthly numbers of the felt and unfelt earthquakes of which *PS*-times are shorter than 5 *sec.* are shown in Table I. The energy E is determined by the Gutenberg and Richter's formula:

$$\log E = 11.8 + 1.5\,M, \qquad (2)$$

Table I. Monthly numbers of the earthquakes of which *PS*-time is shorter than 5 *seconds* (after the Ooshima Weather Station).

Year Month	1950	1951	1952
Jan.	—	—	1
Feb.	—	—	2
Mar.	1	—	1
Apr.	—	—	—
May	1	1 (I)	—
June	1	—	—
July	1	—	—
Aug.	6 (II, II, I, I, II, I)	3	1
Sept.	—	—	—
Oct.	1	2	22 (incl. I, II)
Nov.	2 (incl. II)	1	3
Dec.	—	4	102 (incl. II, I)

Table II. Felt local shocks observed at the Ooshima Weather Station.

P (J. S. T.)	Intensity	$P\sim S$	$\varDelta$	A	M	$\log E$
d h m		*sec.*	*km*	μ		
1950 Jan. 4 03 40	II	—	—	—	—	(17)
5 01 41	II	—	(12.6)	113.0	4.63	16.4
5 04 48	I	0.9	6.3	—	—	(16)
5 11 08	I	0.9	6.3	—	—	(16)
5 18 55	II	—	—	—	—	(17)
25 21 13	I	0.7	4.2	—	—	(16)
Nov. 25 10 26	II	1.9	13.3	305.4	6.26	18.1
1951 May 28 17 32	I	3.1	21.7	70.1	5.94	17.7
1952 Oct. 4 04 45	I	2.4	16.8	38.5	5.21	17.0
4 19 41	II	2.8	19.6	205.2	6.50	18.3
Dec. 15 00 55	II	2.5	17.5	84.0	5.77	17.6
15 06 44	I	2.4	16.8	49.4	5.37	17.2

where M is the instrumental magnitude. The energy of the felt volcanic earthquakes obtained by eq. (2) is also shown in Table II and Fig. 1 while the writer estimates the energy of the unfelt shock at the order of 10^{15} *ergs* as he has done in the previous paper.

3. Energy accompanied by the lava-flows.

During the 1950-51 activity, fluidal lavas over-flowed from the central pit to the crater and even to the caldera. Their distributions are tabulated in Table III referring to various reports. As for the depth of the magma-reservoir of this volcano, T. Rikitake[3] presumed it to be about 5.5 *km* by analysing the changes in geomagnetic dip during the period from July to Sept., 1950. This value is also acceptable from geological standpoints. The possible error in this value would not seriously affect the results of the various estimations which will be made hereafter. Assuming that the magma-reservoir is situated at a depth of 5.5 *km* under the volcano, the potential energies required to push up the lavas to the earth's surface are estimated as shown in Table IV and Fig. 1. On the other hand, kinetic energy of the fluidal motion of lava-flows is ignored because their velocity is small enough in the crater-vent.

Table III. Ejected lavas in the 1950-51 eruption.

Site	1950	1951	Total		
			Volume	Density	Mass
Central pit	9.8×10^6 *tons*	0	$3.66\times10^6 m^3$	2.7	9.8×10^6 *tons*
Cinder cone	6.2 〃	0	3.62 〃	1.7	6.2 〃
Crater bottom	33.4 〃	8.3×10^6 *tons*	15.44 〃	2.7	41.7 〃
Nomashi flows	1.3 〃	11.3 〃	5.05 〃	2.5	12.6 〃
Senzu flow	1.1 〃	4.5 〃	2.25 〃	2.5	5.6 〃
Total	5.2×10^7 *tons*	2.4×10^7 *tons*	$3.0\times10^7 m^3$		7.6×10^7 *tons*

Here, the daily kinetic work done by lifting the lava, or in other words, the power is obtained as shown in Table IV, where 1 *horsepower* is expressed as 6.45×10^{11} *erg./day*. As seen from the table, the volcano had an enormous power all through the period. The fact leads the writer to the following speculation on the beginning stage of eruptions: The work required to carry the fluidal lava through the pit from the magma-reservoir up to the crater vent will be easily obtained

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[3] T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 161.

Table IV. Mass and energies of ejecta.

Period	Ejected Mass Integrated Sum	Potential Energy		Thermal Energy Integrated Sum
		Integrated Sum	Power	
1951 July 16 ~ Aug. 14	1.4×10^{7} *tons*	7.5×10^{21} *ergs*	2.5×10^{20} *ergs/day*	1.8×10^{23} *ergs*
~ Aug. 31	3.5 〃	1.9×10^{22}	7.1 〃	4.5 〃
~ Sept. 13	5.0 〃	2.7 〃	6.0 〃	6.3 〃
~ Sept. 24	5.2 〃	2.8 〃	1.3 〃	6.6 〃
1951 Feb. 4 ~ Feb. 27	1.7×10^{6}	9.2×10^{20}	3.8×10^{19}	2.1×10^{22}
~ Mar. 25	1.5×10^{7}	8.1×10^{21}	2.7×10^{20}	2.0 〃
~ Mar. 31	2.0 〃	1.1×10^{22}	5.0 〃	2.6 〃
~ May 6	2.2 〃	1.2 〃	2.8×10^{19}	2.7 〃
June 5 ~ June 28	2.4×10^{7}	1.3×10^{22}	4.1×10^{19}	3.0×10^{23}
1954 Jan. 27	$8\ \times10^{5}$	1.6×10^{20}	7.7×10^{20}	6.7×10^{21}

in the following, provided the friction in the pit is neglected. Assuming that the density of lava is 2.3 *gr./cc* and the sectional area of the pit is 100 m^2 (the diameter of the vent observed in Sept. 1950 was about 5 *m*), the potential energy required to fill up the pit with lavas is estimated at 4.0×10^{23} *ergs*. If we assume a value of the power such as is obtained in Table IV, it is probably possible that activity of magma-reservoir reaches the earth's surface in only a day or less. Although no definite value of the power of volcanic action is known at the beginning stage of eruption, it seems of interest and importance that the activity that takes place in the reservoir may come up with a fairly large speed such as a few *kilometers* a day as far as the resistance in the pit is disregarded. In fact, no forerunning phenomena were apparent previous to the 1950 eruption, while the volcanic tremors whose origins are deemed to be situated near the surface began to occur only 8 *minutes* before the eruption. These facts would suggest that the lava came up quickly without causing any marked effects such as forerunning earthquakes.

Next, we must take into account the thermal energy transported by the lavas which plays the most important role in energetics of the volcanic activities as discussed in the previous paper. If we take the specific heat of the basaltic lava as 0.25 *cal./gr.°C* the temperature of the lava as 1,000°*C* and the heat of fusion as 50 *cal./gr.*, the thermal energy carried away through the vent of the volcano is to ordinary temperature estimated as follows:

$$E_{th}=M(1000^{\circ}C\times 0.25\,cal./gr.^{\circ}C+50\,cal./gr.)J \quad (ergs) \qquad (3)$$

where M is the mass of ejected lava and J is the equivalent work of heat. The sums of the thermal energy integrated for each period are also shown in Table IV and Fig. 1.

4. Energy released in other forms.

In the previous sections, the writer has been estimating the amount of the energies which are released in various ways in connection with volcanic activity, all of which can be estimated quantitatively provided we can conduct proper observations. But there may be energies released in other forms which are really difficult to observe, as they are lost by heat-conduction and gas-expansion from the reservoir to the vent of the volcano. The only way to estimate this sort of energy would be to subtract the known energies such as have been examined in the preceding sections from the energy supplied to the reservoir.

Fortunately, the order of the energy which is supplied to the reservoir in the course of an activity of the volcano can be approximately inferred from geomagnetic studies: During the early period of the 1950 eruption, from July to September, T. Rikitake observed anomalous changes in geomagnetic dip-angle associated with the activity. He concluded that the changes are likely to be caused by an apparent magnetic dipole situated just beneath the volcano at a depth of 5.5 *km* with a magnetic moment amounting to 6.3×10^{11} *emu*, the direction of the polarization of the dipole being nearly opposite to that of the earth's magnetic field there. The demagnetization, which is suggested by the occurrence of such a dipole, seems to be due to the rise in temperature in the said region associated with the eruption. As is the case of the 1953–54 eruption, the amount of heat that is necessary for the demagnetization observed by Rikitake in 1950 is estimated at about 2.6×10^{18} *cal.* (1.1×10^{26} *ergs*), though thermal processes relating to these changes can't be discussed in detail because no continuous observation of geomagnetism was available in Ooshima at that time.

Here, it may be reasonably assumed that the energy supplied to the magma-reservoir in the case of the 1950 eruption is at least of the same order of magnitude as the above figures. As fully discussed in the last section, the energy released from the volcano in such a form that we could observe and estimate quantitatively was estimated at 4.4×10^{23} *ergs*. The residue must be dissipated by thermal conduction, convection and radiation and expansion of gases from the reservoir as discussed previously.

On the other hand, S. Murauchi[4] made a few observations of the amount of the gases (almost composed of water vapour) emitted from Volcano Mihara in the 1950-51 eruption. He has given the following figures, though not so accurately.

	Emitted water vapour	Ejected lava
Sept. 1, 1950	2.1 *tons/sec.*	15.9 *tons/sec.*
〃 17, 1950	1.8 〃	12.6 〃
Feb. 11, 1951	0.055 〃	0.50 〃

According to this result, it may be said that water vapour amounting to more than 10^4 *tons* per day was emitted in the active stage of the eruption. If we take the temperature of water vapour at the vent of the volcano as 500°*C*, thermal energy carried away by the vapour is estimated at about 10^{13} *cal.* ($\approx 10^{20}$ *ergs*) per day. Thus, the emission of gases from the volcano would certainly play a rather important role in its energetics though we have never had continuous observation of emitted gases on the volcano. This sort of observation would be difficult to carry out on an actual volcano, because we usually find there many vents or cracks which are emitting gases all the time. In order to complete energetics of active volcanoes, however, we should put much stress to the observation of this kind though many difficulties are to be overcome.

5. Discussion.

On examining the results shown in Fig. 1, the writer reaches the following conclusions which are almost the same as those of 1st Paper.

1) The total energy emitted as volcanic tremors was almost the same order in magnitude as that of local shocks which occured during the period.

2) Local shocks, either felt or unfelt, scarcely occured when volcanic tremors are prevailing. This fact would suggest that an activity in

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4) S. MURAUCHI, *Bull. Natur. Sci. Mus.*, **20** (1953), 70.

the deeper interior of the volcano does not occur simultaneously with that near the surface.

3) It is made clear that the thermal energy such as the heat carried away by lavas and gases occupies the main part of the energy which comes out from the volcano, while the amount of the other energies of tremors and local shocks and potential energy, is definitely smaller than the thermal one.

PART II.

Activities of a Number of Volcanoes in Japan and Indonesia in the Past.

A number of geophysicists have hitherto discussed magnitude or energy of particular explosions especially those of the *Vulcanian*-type volcanoes. For example, T. Minakami[5] studied in great detail the explosions and related phenomena on Volcano Asama. Meanwhile, T. Matuzawa[6] estimated various energies released by the great 1914 eruption of Volcano Sakurazima and pointed out that the thermal energy accompanied by the lava-flows was the largest.

Recently, H. Tsuya[7] proposed an intensity scale of volcanic eruption which classifies intensity of volcanic activity into ten grades, 0–IX, assuming that the intensity is proportional to the potentiality of volcanic gases to drive their container, either fluent or fragmentary, hence proportional to the total volume of ejecta. Then he divided the volcanic ejecta into three types, essential lava-flow (A-type), fragmentary ejecta only (B-type) and essentially old detritus ejected in the past (D-type).

On taking into account the results obtained in Part I of this paper, the writer would like to extend Tsuya's classification by volume of ejecta to one by energy sent out by volcanic activities. As a consequence of this investigation, several examples of volcanic activities in Japan and Indonesia will be illustrated in the following.

1. Classification and estimate of volcanic energies.

Generally speaking, the energy of volcanic activities is spent in the following ways:

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[5] T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **20** (1942), 431.

[6] T. MATUZAWA, *Zisin-gaku* (in Japanese) (1950), 363.

[7] H. TSUYA, *Bull. Earthq. Res. Inst.*, **33** (1955), 341.

1). In producing volcanic tremors;

2). In producing local earthquakes;

3). In breaking the material of the mountain-mass;

4). In ejecting the material from the interior of volcano such as lava-flows, fragmentary ejecta and gases;

5). In producing disturbances in the air or sea.

The first two energies released as volcanic tremors and local shocks were already discussed in detail for the case of Volcano Mihara.

The energy spent in the third way is, at the lowest, equal to elastic strain energy which may be contained in the rock-mass before it ultimately breaks down, namely,

$$E_e = \frac{1}{2} Ye^2 V, \tag{4}$$

where Y, e and V represent Young's modulus, ultimate strain of the rock and volume of the destroyed mountain-mass respectively. Y may be supposed to be $5 \times 10^{11}\, dyne/cm^2$ on referring to F. Birch's[8] paper. According to C. Tsuboi's[9] studies on the crustal movemnts in Japan and experimental studies on rocks, e may be safely assumed to be 10^{-4}.

The fourth energy is accompanied by materials including fluidal lavas, solid ejecta and gases and classified into three subgroups;

Potential energy, kinetic energy and thermal energy.

Potential energy will be estimated if the depth of the magma-reservoir is given. The depth is generally believed to amount to several *kilometers* beneath the volcano. It has been demonstrated by the writer that geomagnetic methods are useful for presuming the depth of the reservoir, especially on the volcano composed of basaltic rocks.

Kinetic energy consumed by eruptions is determined by the initial velocity of ejecta at the vent of the volcano which was closely studied by T. Matuzawa. On Volcano Asama, T. Minakami established the relation between the explosion energy and the amplitude of the volcanic earthquakes observed at a station on the foot of the volcano.

The higher the temperature of ejecta is, the more important is the thermal energy. And ejecta composed of old detritus is almost unrelated with thermal energy. If the ejected lava has a temperature of almost 1,000°C and is fluidal, the total heat lost by lava crystallizing and cooling to ordinary temperature is approximately estimated by

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[8] F. BIRCH, *Handbook of Physical Constants* (1942), 73.

[9] C. TSUBOI, *Bull. Earthq. Res. Inst.*, **11** (1933), 275.

$$E_{th}=M(1000°C\times 0.25\,cal./gr.°C+50\,cal./gr.)J \qquad (ergs), \qquad (5)$$

where the specific heat and the latent heat of lava is assumed to be $0.25\,cal./gr.°C$ and $50\,cal./gr.$ respectively. And if the ejecta has a temperature of $500°C$, the heat-loss by it is given by

$$E_{th}=M(500°C\times 0.20\,cal./gr.°C)J \qquad (ergs). \qquad (6)$$

In the following discussion, the writer assumes that the temperatures of A- and B-type ejecta is $1,000°C$ and $500°C$ respectively.

As for gases, thermal energy accompanied by them was discussed for the case of the eruption of Volcano Mihara in Part I. In short, it is not possible to estimate accurately this sort of energy.

Lastly, the energy of producing distrubances in the air or sea is found to be so small that we can neglect it completely compared with the other energies.

2. Examples of the estimation of volcanic energies.

During these scores of years, early pioneers in geophysics and geology have made quantitative and reliable observations of various volcanic activities in Japan. The writer's analyses of energetics of Japanese volcanoes are altogether due to their work. In discussing the eruptions of Indonesian volcanoes the writer refers to " Catalogue of the Active Volcanoes of the World " which is the standard authority concerning active volcanoes.

The following examples of estimation of the volcanic energies will be based upon the principles obtained by the previous studies. It turns out, however, that we may take into account, for order-of-magnitude estimates, only thermal energy because energies of other kinds do not contribute very much to the total sum of the energy.

Tambora, Sumbawa 1815

On April 5, 1815 thundering explosions were heard even at distances of 1250 and 1400 km. The paroxysmal eruptions lasted from April 10 to 12. Detonations were heard at distances of 1500 and 1750 km. Rock fragments of 2 cm in diameter and a few of 15 cm have fallen at a distance of 40 km from the crater.

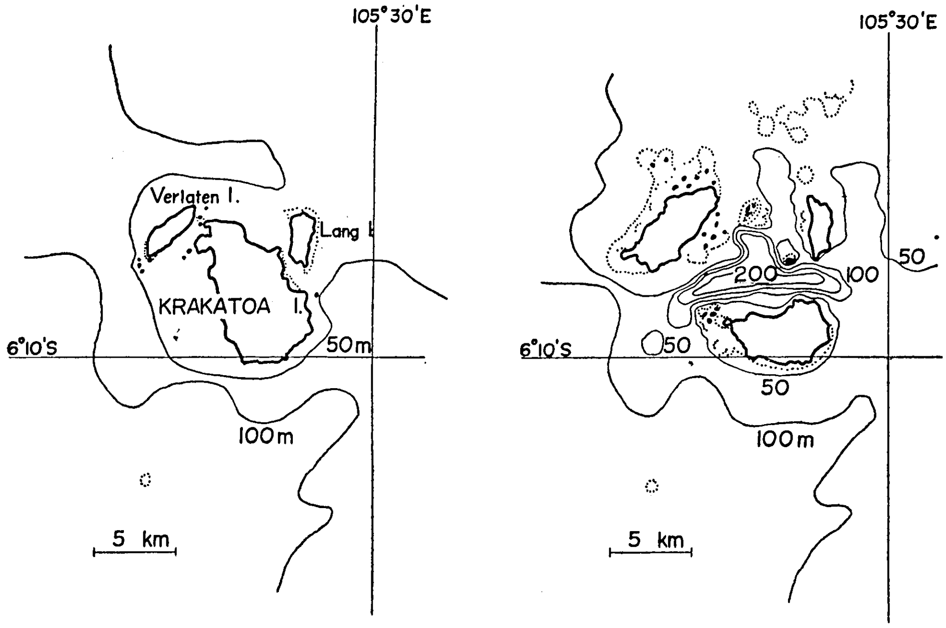
Verbeek estimated the amount of ejecta at 150 km^3, Petroeschevsky at 100 km^3, while Pannekoek van Rheden calculated it at only 30 km^3.

Here, the writer adopts 100 km^3 as the amount of ejecta and estimates its thermal energy which is clearly the largest one of the various energies:

$$E_{th}=10^2\times10^{15}\,cc\times2.0\,gr./cc\times0.20\,cal./gr.^\circ C\times500^\circ C\times J=8.4\times10^{26}\,ergs.$$

Krakatoa, Sunda Str. 1883

According to the Report of the Krakatoa Committee (1886), a part of the mountain amounting to at least 5.6×10^{15} *cc* in volume disappeared in the great 1883 eruption. The writer also made a rough estimation of the volumes of Krakatoa before and after the eruption with the aid of the two sheets of bathygraphic chart in the Report;



(a) (b)

Fig. 2. Bathygraphic charts around Krakatoa Island.
a) before the 1883 eruption
b) after the 1883 eruption

Before the eruption: volume above sea-level 5.9×10^{15} *cc*,

After the eruption: ,, ,, 3.6×10^{15} *cc*

And the volume under the sea-level blown off by the eruption was about 7.7×10^{14} *cc*. Therefore, total volume of the devastated mountain-mass would be about $3.1\times 10^{15}\,cc$. Here, we may adopt the figure $5\times 10^{15}\,cc$ as the ejected volume.

After F. Von Wolf, the maximum pressure of the explosion was $425\,atm$. Initial velocity of ejecta is to be obtained by the following assumed relation

$$p=\frac{1}{2}\rho v_0^2$$

where ρ is the mean density of ejecta. If ρ is taken as $2.3\,gr./cc$, v_0 becomes $193\,m/sec$. Thus, the kinetic energy of the eruption is obtained as

$$E_k=\frac{1}{2}\times 2.3\,gr./cc\times 5\times 10^{15}\,cc\times(1.93\times 10^4\,cm/sec.)^2=2.1\times 10^{24}\,ergs$$

at most.

Assuming that only the temperature of the missing mass under the sea-level was $500°C$, the thermal energy accompanied by it is estimated as

$$E_{th}=7.7\times 10^{14}\,cc\times 2.3\,gr./cc\times 500°C\times 0.20\,cal./gr.°C\times J=8.4\times 10^{24}\,ergs,$$

so that we see that the total energy sent out at the time of the eruption was as much as $10^{25}\,ergs$.

Sakurazima, Japan

a) 1914

The volume of the overflowed lavas was estimated at $1.5\,km^3$ and that of the ejected ash and pumice at $0.62\,km^3$, while the volume of the land-depression around the volcano was proved to be $1.4\,km^3$ by the repeated levelling-surveys.

T. Matuzawa evaluated the various energies associated with eruption as follows:

Potential energy accompanied by lava	$1.9\times 10^{22}\,ergs$
Thermal ,, ,,	4.6×10^{25} 〃
Kinetic energy of ash and pumice ($v_0=100\,m/sec.$)	7.5×10^{22} 〃
Thermal ,, ,,	6.2×10^{24} 〃

He concluded that the total energy sent out by this eruption was of the order of $10^{25}\,ergs$.

b) 1946

After T. Nagata, S. Sakuma and N. Fukushima$^{10)}$, the fluidal lava ejected in this eruption totaled to $8.3\times10^{13}\,cc$ in volume.

The amount of the thermal energy accompanied by the lava-flows was about $2.1\times10^{21}\,ergs$.

Huzi (san), Japan 1707

H. Tsuya$^{11)}$ estimated the volume of the ejecta which was B-type in his classification, at $8.5\times10^{11}\,cc$.

The thermal energy released by the eruption was roughly given as

$$E_{th}=8.5\times10^{11}\,cc\times2.0\,gr./cc\times500^{\circ}C\times0.20\,cal./gr.^{\circ}C\times J=7.1\times10^{21}\,ergs$$

Asama (yama), Japan

a) 1783

The volumes of the ejecta by the eruption were estimated as follows;

Oni-oshidashi lava-flow	$1.7\times10^{11}\,cc$	(after S. Aramaki)
Kambara nuée ardente	$0.1\text{–}0.01\times10^{11}\,cc$	,, ,,
Agatsuma ,, ,,	$1.0\times10^{11}\,cc$	,, ,,
Pumice	$1.7\times10^{11}\,cc$	(after T. Minakami)

The thermal energies accompanied by the ejecta of each kind are

Lava-flow $1.7\times10^{11}\times2.5\times(1000\times0.25+50)\times J=5.4\times10^{21}\,ergs$
Nuée ardente $1.1\times10^{11}\times2.0\times(1000\times0.25+50)\times J=2.8\times10^{21}\,ergs$
Pumice $1.7\times10^{11}\times0.8\times500\times0.2\times J=5.9\times10^{23}\,ergs$

The total thermal energy becomes about $8.8\times10^{21}\,ergs$, while T. Minakami$^{12)}$ estimated the kinetic energy of the explosion as

$$E_k=\frac{1}{2}\times1.7\times10^{11}\,cc\times0.8\,gr./cc\times(2.5\times10^{4}\,cm/sec.)^2=4.4\times10^{22}\,ergs.$$

b) 1935

After T. Minakami$^{13)}$, the total mass of the lava ejected in this ex-

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10) T. NAGATA, S. SAKUMA and N. FUKUSHIMA, *Bull. Earthq. Res. Inst.*, **24** (1946), 162.

11) H. TSUYA, *loc. cit.*, 7).

12) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **20** (1942), 93.

13) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **20** (1942), 82.

plosion amounted to $4.5\times10^{12}\ gr.$, so that the thermal energy is obtained as

$$E_{th}=4.5\times10^{12}\ gr.\times1000°C\times0.25\ cal./gr.°C\times J=4.8\times10^{22}\ ergs.$$

c) 1938

According to T. Minakami's[14] study, the total mass of the ejecta which was B-type, was $3.8\times10^{11}\ gr.$ and the initial velocity of the ejecta at the vent was $212\ m/sec.$ From these data he obtained the kinetic energy of explosion as $1.7\times10^{21}\ ergs.$

On taking into account Minakami's statement that the temperature of a volcanic bomb was about 800°*C* at the time of its landing, the total thermal energy accompanied by all the ejecta is estimated roughly at

$$E_{th}=3.8\times10^{11}\ gr.\times1000°C\times0.25\ cal./gr.°C\times J=4.0\times10^{21}\ ergs.$$

Mihara (yama), Ooshima, Japan

Volcano Mihara is a typical *Strombolian* volcano as discussed in the previous part of this paper. The thermal energy released by the essential lava flows in the cases of several eruptions is estimated as follows;

a) **1777–78** $3.4\times10^{13}\ cc\times2.5\ gr./cc\times(1000°C\times0.25\ cal./gr.°C+50\ cal./gr.)J=1.0\times10^{21}\ ergs.$

b) **1912** $2\times10^{10}\ cc\times2.5\ gr./cc\times1000°C\times0.2\ cal./gr.°C\times J=6.3\times10^{20}\ ergs.$

c) **1950–51** $3.0\times10^{13}\ cc\times2.5\ gr./cc\times(1000°C\times0.25\ cal./gr.°C+50\ cal./gr.)J=9.4\times10^{23}\ ergs.$

d) **1954** $4\times10^{11}\ cc\times2.5\ gr./cc\times(1000°C\times0.25\ cal./gr.°C+50\ cal./gr.)J=1.3\times10^{22}\ ergs.$*

Torishima, Japan 1939

The writer estimates the volume of the ejected lava in the 1939

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[14] T. Minakami, *Bull. Earthq. Res. Inst.*, **20** (1942), 86.

* *Corrigenda* to 1st Paper, *Bull Earthq. Res. Inst.*, **34** (1956). Page 193, line 20. Read 6.7×10^{21} for 6.7×10^{22}. In 1st Paper, the writer adopted $0.20\ cal./gr.°C$ as the specific heat of lava and neglected the latent heat.

eruption at $3.1\times10^{13}\,cc$. The thermal energy accompanied by the fluidal lava is obtained as

$$\begin{aligned}E_{th}&=3.1\times10^{13}cc\times2.5\,gr./cc\times(1000°C\times0.25\,cal./gr.°C+50\,cal./gr.)J\\&=9.7\times10^{23}\,ergs.\end{aligned}$$

Komagatake, Japan 1928

According to S. Tsuboi and H. Tsuya[15], the initial temperature of pumice ejecta was presumed to be not conspicuously higher than $730°C$. On referring to their result of the observation of the ejecta, the writer estimates its volume at $5.1\times10^{13}\,cc$. The thermal energy released by the ejecta is obtained as

$$E_{th}=5.1\times10^{13}\,cc\times1.5\,gr./cc\times800°C\times0.25\,cal./gr.°C\times J=5.6\times10^{23}\,ergs.$$

Miyakeshima, Japan 1940

According to S. Omote[16], the area of the parasitic cones was $2.7\times10^5\,m^2$ and that of the lava-flow was $2.9\times10^5\,m^2$. The volumes of the parasitic cones and the lava-flow respectively 11.6×10^6 and $7.5\times10^6\,m^3$. The total volume of erupted lava amounted to $19.1\times10^6\,m^3$, the same order of magnitudes as that of lava erupted in the activities of 1874, as calculated by H. Tsuya[17]. Assuming the bulk density of the new ejecta to be $2.0\,gr./cc$, the total weight of the new ejecta was estimated, without serious error, at $3.8\times10^7\,tons$.

The thermal energy accompanied by the new ejecta is obtained as

$$E_{th}=3.8\times10^{13}gr.\times(1000°C\times0.25cal./gr.°C+50cal./gr.)J=4.8\times10^{13}\,ergs.$$

Bandaisan, Japan 1888

According to S. Sekiya aud Y. Kikuchi[18], *the most striking feature in the whole of this eruption was the deluge of rock and earth. Notwithstanding the violence of the phenomena, and the completeness with which the mountain was destroyed, the nature of the eruption was comparatively simple. The destructive agency was merely the sudden expansion of imprisoned steam, unaccompanied by lava flows or pumice ejection. By far the greater volume was comparatively in a dry state, being moistened only by condensing steam, and must have derived its fluid or*

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[15] S. TSUBOI and H. TSUYA, *Bull. Earthq. Res. Inst.*, **8** (1930), 317.

[16] S. OMOTE, *Bull. Earthq. Res. Inst.*, **19** (1941), 388.

[17] H. TSUYA, *Zisin* (in Japanese), **12** (1940), 473.

[18] S. SEKIYA and Y. KIKUCHI, *Trans. Seism. Soc. Japan*, **8** (1890), Part II, 153.

semi-fluid properties from a rapid process of pulverization. They estimated the volume of the mountain destroyed at $1.2 \times 10^{15}\,cc$ and deemed the density of the mountain as $2.33\,gr./cc$. On the other hand, T. Matuzawa[19] obtained the initial vertical velocity of ejecta at the creater as $172\,m/sec$.

Except the energy necessary for projecting the ejecta, the energy necessary for breaking down the mountain-mass is equal to the elastic strain energy which is shown by equation (4):

$$E_e = 1/2 \times 5 \times 10^{11}\,dyne/cm^2 \times (10^{-4})^2 \times 1.2 \times 10^{15}\,cc = 3.0 \times 10^{18}\,ergs.$$

If we assume the initial velocity of all ejecta as $170\,m/sec.$, the kinetic energy will be obtained as

$$E_k = 1/2 \times 1.2 \times 10^{15}\,cc \times 2.33\,gr./cc \times (1.7 \times 10^{4}\,cm/sec.)^2 = 4.1 \times 10^{23}\,ergs.$$

Assuming the sliding down of the collapsed material by gravity, we get the vertical and horizontal displacements of the mass as 300 and 2,500 m respectively in Fig. 3. Then we obtain the velocity at the low-lying district from the following relation neglecting friction in sliding;

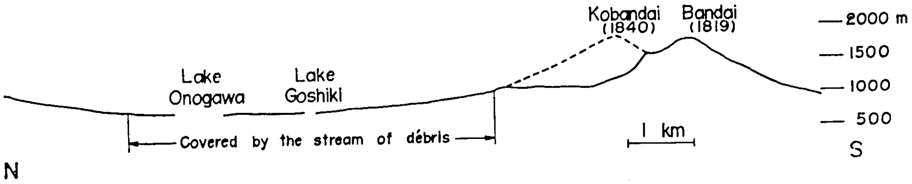

Fig. 3. The 1888 eruption of Bandaisan
(Mt. Kobandai was destroyed by this eruption).

$$\rho g h = 1/2 \rho v^2\,.$$

Using the abovementioned values, we obtain velocity of the mudflow as $280\,km/hour$. Sekiya and Kikuchi's report saying that the observed average velocity was about $77\,km/hour$, seems to suggest the sliding down of the meterial by gravity but there must have been the driving agency in the initial motion.

After all, the order of magnitude of the total energy associated with the eruption might be $10^{23}\,ergs$.

Guntur, Java 1843

The eruptions were generally of short duration, throwing out ashes

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[19] T. MATUZAWA, *Bull. Earthq. Res. Inst.*, **11** (1933), 343.

and glowing stones. Sometimes however enormous quantities were emitted (*7.8 million* m^3 *in 1843*). The thermal energy accompanied by the ejecta is estimated at

$$E_{th}=7.8\times10^{12}\,cc\times2.0\,gr./cc\times500^\circ C\times0.20\,cal./gr.^\circ C\times J=6.5\times10^{22}\,ergs.$$

Pematang Bata, Sumatra 1933

Only old material was thrown up, maximal 1100 m high, while the the steam clouds rose to more than 2,000 m height. In total 0.210 km^3 *of mud was thrown out.* The initial vertical velocity of thrown up mud is obtained from the following formula,

$$v_0=\sqrt{2gh}=\sqrt{2\times980\times1.1\times10^5}=1.47\times10^4\,cm/sec.$$

The kinetic energy of this steam eruption is estimated as

$$E_k=\frac{1}{2}\times2.1\times10^{14}\,cc\times2.0\,gr./cc\times(1.4\times10^4\,cm/sec.)^2=4.5\times10^{22}\,ergs.$$

Una Una, Celebes 1898

2.2 million m^3 *ash and mud was scattered over* $3.03\times10^5\,km^2$. *The central cone originated between 1898 and 1900, probably above a rising lava plug.* Assuming the density of the ejecta as 1.5 $gr./cc$ and the temperature as 500°C, the thermal energy released by the ejecta is obtained as

$$E_{th}=2.2\times10^{12}\,cc\times1.5\,gr./cc\times500^\circ C\times0.20\,cal./gr.^\circ C\times J=1.8\times10^{22}\,ergs.$$

Adatarasan, Japan 1900

According to F. Omori's[20] description, the writer estimates the volume of blown rocks and ashes at $1.1\times10^{12}\,cc$. Judging from the fact that abrupt descend of hot ashes along the slope of the volcano caused casualties, the temperature of the ejected ashes is assumed to have been about 300°C at the lowest. Then, the thermal energy released by the eruption is obtained as

$$E_{th}=1.1\times10^{12}\,cc\times2.3\,gr./cc\times300^\circ C\times0.20\,cal./gr.^\circ C\times J=6.4\times10^{21}\,ergs.$$

Azumasan, Japan 1893

F. Omori's[21] estimation of the volcanic energy in the 1893 eruption

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[20] F. OMORI, *Rep. Imp. Earthq. Inv. Comm.*, No. 35 (in Japanese).

[21] F. OMORI, *Seism. Journ. Japan*, **19** (1894), 1.

was as follows: *The mud and ashes seemed to have been projected upwards to a height of about 1 km. We have no means of finding the height to which the centre of gravity of the whole projected mass was raised. Let us assume this height to be 100 m, which probably would not be much greater than the actual value. Then, since the total volume of rock and mud projected is* $5\times 10^5\,m^3$, *the work done would be*

$$100\,m\times 5\times 10^5\,m^3\times W=5\times 10^7\times W\,kg\cdot m,$$

W being the weight of $1\,m^3$ *of rock and mud.*

The energy of an earthquake vibration is, when the motion is of simple harmonic type, given by the formula $1/2\,mv^2$ *in which v is the maximum velocity of the earth particle, and m is the whole of the disturbed mass. In the case of the earthquake caused by the explosion under consideration, we may probably, without much mistake, put the mean amplitude of motion at 1/10 mm, and the period at 1/10 sec. If we further suppose the whole area of disturbance, 1,300* km^2 *extent, to have been at any instant of time disturbed to a uniform depth of 1/4 km, the energy of vibration is*

$$\frac{1}{2}\times 1.3\times 10^9\,m^2\times 250\,m\times\frac{4\pi^2(1/10\times 1/1000\,m)^2}{(1/10\,sec.)^2}\times W'=6.4\times 10^6 W'\,kg\cdot m$$

W' *being the mean weight of* $1\,m^3$ *of the surface earth. If we assume* $W'=W$, *the works done in the above two ways are together equal to* $5.6\times 10^7 W\,kg\cdot m$. *As the energy of explosion has been spent in doing other works,* $6\times 10^7 W\,kg\cdot m$ *may be less than the actual amount of the whole work done. If we put W to be 2,300 kg, the work done by the energy of the explosion is about* $1.4\times 10^{11}\,kg\cdot m$ *(*1.4×10^{19} *ergs).*

According to T. Matuzawa[22], the initial velocity of the volcanic bombs was 148 *m/sec.* Therefore, the kinetic energy of the explosion is estimated as

$$E_k=\frac{1}{2}\times 5\times 10^{11}\,cc\times 2.3\,gr./cc\times(1.48\times 10^4\,cm/sec.)^2=1.3\times 10^{20}\,ergs.$$

Assuming the temperature of the ejecta to be 100°*C*, the thermal energy released by the ejecta is estimated at

$$E_{th}=5\times 10^{11}\,cc\times 2.3\,gr./cc\times 100°C\times 0.20\,cal./gr.°C\times J=1.0\times 10^{21}\,ergs$$

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[22] T. MATUZAWA, *loc. cit.*, 15).

Total energy of the eruption is deemed to be order of magnitude 10^{21} *ergs*.

Tokachidake, Japan

According to F. Tada and H. Tsuya's[23] report, volume of ejected material (old detritus and new volcanic bombs) was $1.3\times10^{10}\,cc$ and volume of the destructed part of the old central cone which descended along the slope of the mountain as the mudflow, was about $2.7\times10^{12}\,cc$. S.T. Nakamura[24] calculated the initial velocity of the mud-flow as $80\,m/sec$. On referring to the above observations, the thermal energy accompanied by the ejecta is estimated at

$$E_{th}=1.3\times10^{10}\,cc\times2.0\,gr./cc\times500C^{\circ}\times0.20\,cal./gr.{}^{\circ}C\times J=1.1\times10^{20}ergs.$$

And elastic strain energy stored in the destructed mountain-mass is obtained as

$$E_e=\frac{1}{2}\times5\times10^{11}\,dyne/cm^2\times(10^{-4})^2\times2.7\times10^{12}\,cc=6.8\times10^{15}\,ergs.$$

The kinetic energy of the mud-flow is estimated at

$$E_k=\frac{1}{2}\times2.7\times10^{12}\,cc\times2.0\,gr./cc\times(8\times10^3\,cm/sec.)^2=1.7\times10^{20}\,ergs.$$

Thus, the total energy of the eruption is regarded as 2.8×10^{20} *ergs*.

Myoozin Reef near the Bayonnaise Rocks, Japan 1952

S. Murauchi[25] observed the sea-waves which had been caused by the eruption of the submarine volcano at Myoozin Reef on Sept. 23 and obtained the wave-height as $2\,m$ at the distance at about $1{,}500\,m$ from the centre of the explosion. He estimated the energy of the one submarine explosion to be about 10^{18} *ergs* after the analogy of the results obtained by the experiments of the underwater explosion of atomic bombs in the Pacific. The total energy of this submarine eruption may be regarded as the order of magnitude 10^{19} *ergs* at the least.

Kusatsu-Shiranesan, Japan 1932

After H. Tsuya[26], volcanic ash fell more than $3\,cm$ in thickness

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[23] F. TADA and H. TSUYA, *Bull. Earthq. Res. Inst.*, **2** (1927), 49 (in Japanese).

[24] S.T. NAKAMURA, *Chikyu* (in Japanese), **6** (1926), 79.

[25] S. MURAUCHI, *Zisin* (in Japanese), [ii], **5** (1952), 158.

[26] H. TSUYA, *Bull. Earthq. Res. Inst.*, **11** (1933), 82.

over a radius of 410 m around the crater and the solid ejecta consisted wholly of non-incandescent detritus, all coming under the title "accessory ejecta". The volume of the ejecta is roughly estimated at

$$\pi(4.1\times10^4\ cm)^2\times3\ cm=1.6\times10^{10}\ cc.$$

The initial velocity of the volcanic bombs was presumed as 128 $m/sec.$ by T. Matuzawa[27]. Then the kinetic energy of the ejecta is obtained as follows assuming the density of the volcanic ash to be 1.2 $gr./cc.$

$$E_k=\frac{1}{2}\times1.6\times10^{10}\ cc\times1.2\ gr./cc\times(1.28\times10^4\ cm/sec.)^2=1.6\times10^{18}\ ergs.$$

3. Conclusion.

All the examples of volcanic eruptions discussed in the previous section are summarized in Table V where the Tsuya's intensity scale is considered together. As seen in Table V, it is true that the amount of the released energy by volcanic activities depends on the volume of ejecta, but physical (especially thermal) conditions of the ejecta play more important role in energetics in active volcanoes. For an example, the volume of ejecta in the 1888 eruption of Volcano Bandai (san) was very enormous while its total volcanic energy is estimated at rather low value. In fact, the ejecta in this eruption, strictly speaking, was almost the collapsed mountain-mass unaccompanied by the high temperature lava or pumice.

Total energy of a present "large" eruption proved to reach something around $10^{24}\sim10^{25}\ ergs$. This magnitude of energy is comparable to that of a large earthquake. And the lower limit of the total energy in a "eruption" may be speculated to be about $10^{16}\sim10^{17}\ ergs$ while fumarole activities are releasing more minor quantity of the energy.

Discussion concerning the relation between energies of vlocanism and earthquake occurrences will be tried in the next paper.

In concluding, the writer wishes to express his hearty thanks to Dr. T. Rikitake who has given him helpful suggestions in course of the present study. He is also indebted to many senior investigators whose valuable papers he quoted in this report.

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[27] T. MATUZAWA, *loc. cit.*, 19).

Table V. Estimation of volcanic energies on Japanese and Indonesian volcanoes.

Volcano	Year	Ejecta		Total Energy		Tsuya's Intensity scale		Activity
		Volume (*cc*)	Type	(*erg*)	Log.	Vol. of Ejecta (*cc*)	Grade	
Tambora	1815	1×10^{17}	B	8.4×10^{26}	**27**	10^{17}	VIII	○ ↑ ⊠ †
Sakurazima	1914	2.1×10^{15}	AB	4.6×10^{25}	**26**	$10^{16}\sim10^{15}$	VII	○= ↑ ≈> ⊠
Krakatoa	1883	5×10^{15}	B	$\sim10^{25}$	**25**	〃	VII	○ ○° ↑ ⊼
Asama	1783	4.5×10^{14}	AB	8.8×10^{24}	**25**	$10^{15}\sim10^{14}$	VI	○ ↑ ≈> ⇢ ⊠ †
Huzisan	1707	8.5×10^{14}	B	7.1×10^{24}	**25**	〃	VI	○° ↑ ⊠
Sakurazima	1946	8.3×10^{13}	A	2.1×10^{24}	**24**	$10^{14}\sim10^{13}$	V	○= ↑ ≈>
Mihara	1777-8	3.4×10^{13}	A	1.0×10^{24}	**24**	〃	V	○ ↑ ≈>
Torishima	1939	3.1×10^{13}	AB	9.7×10^{23}	**24**	〃	V	○ ↑ ≈> ⊠
Mihara	1950-1	3.0×10^{13}	A	9.4×10^{23}	**24**	〃	V	○ ↑ ≈>
Komagatake	1929	5.1×10^{13}	B	5.6×10^{23}	**24**	〃	V	○ ↑
Miyakeshima	1940	1.9×10^{13}	AB	4.8×10^{23}	**24**	〃	V	○= ≈> ↑ ○
Bandaisan	1888	1.2×10^{15}	D	$\sim10^{23}$	**23**	$10^{16}\sim10^{15}$	VII	○ ⇡ ⤳ ⊠ †
Guntur	1843	7.8×10^{12}	B	6.5×10^{22}	**23**	$10^{13}\sim10^{12}$	IV	○ ↑ ⊠
Asama	1935	2.2×10^{12}	B	4.8×10^{22}	**23**	〃	IV	○ ↑
Pematang Bata	1933	2.1×10^{14}	D	4.5×10^{22}	**23**	$10^{15}\sim10^{14}$	VI	⇡
Una Una	1898	2.2×10^{12}	B	1.8×10^{22}	**22**	$10^{13}\sim10^{12}$	IV	↑ ⤳ ⊠
Mihara	1954	4×10^{11}	A	1.3×10^{22}	**22**	$10^{12}\sim10^{11}$	III	○ ↑ ≈>
Adatarasan	1900	1.1×10^{12}	B	6.4×10^{21}	**22**	$10^{13}\sim10^{12}$	IV	○ ↑ †
Asama	1938	1.5×10^{11}	B	4.0×10^{21}	**22**	$10^{12}\sim10^{11}$	III	○ ↑
Azumasan	1893	5×10^{11}	B	$\sim10^{21}$	**21**	〃	III	○ ↑ †
Mihara	1912	2×10^{10}	A	6.3×10^{20}	**21**	$10^{11}\sim10^{10}$	II	○ ↑ ≈>
Tokachidake	1926	2.7×10^{12}	DB	2.8×10^{20}	**20**	$10^{13}\sim10^{12}$	IV	○ ↑ ⤳ ⊠ †
Myoozin Reef	1952	?	B	$\sim10^{19}$	**19**	?	?	⊼ ↑ †
Kusatsu-Shiranesan	1932	1.6×10^{10}	D	1.6×10^{18}	**18**	$10^{11}\sim10^{10}$	II	○ ↑

Types of ejecta

A: essential lava-flow,
B: fragmentary ejecta only,
D: essentially ejected old detritus.

List of symbols for volcanic activities (after Catalogue of the Active Volcanoes of the World, 1951)

○	Eruption in the central crater	≈>	Lava flow
○°	Eruption in a parasitic crater	⇡	Phreatic explosions
○=	Eruption in a radial fissure	⤳	Mud flow
=	Eruption in a regional fissure	⊼	Submarine eruption
↑	Normal explosions	⊠	Destruction of arable land
⇢	Eruption producing nuées ardentes	†	Casualities

6. 火山活動のエネルギー (第2報)

I. 大島三原山の1950～52年間の活動について

II. 日本及びインドネシヤの諸火山の活動例について

地震研究所　横　山　泉

第1報に続いて，順序は逆であるが，大島三原山の1950～52年間の活動について，エネルギー論的に調べた．結果は第1報のそれと全く同じである．これらの結果を基にして，他の諸火山の活動エネルギーを吟味した．既に先年津屋教授は噴火強度階なるものを提唱したが，これに準じて，信頼性あり且つ定量的な調査報告の存在する日本及びインドネシヤの諸火山の活動について，エネルギーを検討した．尚，稀少文献の報文は煩を厭わず，そのまま引用した．