7. *Energetics in Active Volcanoes. 3rd Paper.*

By Izumi YOKOYAMA,

Earthquake Research Institute.

(Read Nov. 27, 1956.—Received Dec. 31, 1956.)

Summary

The method of estimating energy related to volcanic activity, which has been applied to Volcano Mihara and other volcanoes in the previous papers, is extended to an estimate of total energy required to form a particular volcanic zone such as the Seven Izu Islands. The energy thus obtained is discussed in relation to theories of volcanism and seismicity which have been developed by Verhoogen, Gutenberg, Tsuboi, Bullard and Matuzawa.

1. Introduction.

Energy-problems of earthquakes have been fully studied by many geophysicists. The mutual relation between earthquake occurrences and volcanism is generally conceived by tacit understanding in many respects, but there seems no clue to verify it quantitatively. Energetics of the active volcanoes discussed in the previous papers makes it possible to trace back the volcanic energy to past times. Here, the writer will discuss the meaning of a "volcanic zone" from the standpoint of energetics.

A seismic zone and a volcanic zone generally coexist at limited areas on the earth and these two zones are distributed side by side not intermingling with each other. This fact may be taken as indicating that both are derivatives of the same origin energized from the deep.

Reserving the discussion on the mechanism of earthquake occurrences and volcanism, the writer will consider their energy-release as heat-flow from the deep to the earth-surface.

2. Review of energetics related to volcanic and seismic zones.

Before the writer[1] obtained some conclusions regarding energetics in volcanic activity by the analyses of the recent activities of Volcano

1) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **34** (1956), 185; **35** (1957), 75.

Mihara, J. Verhoogen[2] already formed his opinions on the igneous activities since the Precambrian: He considered volcanic phenomena in their true proportion as compared to the earth as a whole. He estimated the total volume of lava erupted since the close of the Precambrian at $3\times10^{22}\,cm^3$. A present day "large" eruption would amount to something around $10^{15}\,cm^3$ on the average as shown in Table V of 2nd Paper. As regards heat, he pointed out that total amount of the heat required to account for all volcanic activities since that time would be of the order of $4\times10^{25}\,cal.$ taking the total heat carried away by one *gram* of lava crystallizing and cooling from $1000°C$ to ordinary temperature to be 400 *cal.* (the writer deemed it 300 *cal.* in the previous papers). From his estimation, the heat flow radiated by volcanic activities all over the earth-surface during the period will be obtained as

$$\frac{4\times10^{25}\,cal.}{5.08\times10^{18}\,cm^2\times15\times10^{15}\,sec.}=5.2\times10^{-10}\,cal./cm^2\cdot sec. \qquad (1)$$

Volcanic heat represents only a very small fraction of the heat radiated by the earth considering that the average value of the heat flow near the earth-surface is $1.23\times10^{-6}\,cal./cm^2\cdot sec.$ His conclusion is as follows: *These facts suggest that the real problem of volcanoes is not so much to find a suitable source of energy as to provide ways and means by which rather insignificant amounts of heat can be focussed on relatively insignificant volumes of the crust. The orders of magnitude suggest that volcanic activity may result from a coincidence of various factors which may themselves have a small probability by usual standards. In other words, volcanic activity may be something exceptional, and there may be no need to wonder if its manifestations occasionally show somewhat unexpected deviations from the behavior that purely petrological thinking has accustomed us to consider as normal.*

C. Tsuboi[3], who discussed Japanese seismic data including conspicuous and rather conspicuous earthquakes during the period 1912 ～ 40 statistically in time and space, remarked that the earthquakes of which the magnitude is about 6.7 ($10^{22}\,ergs$ in energy estimated by the formula $\log E=11.8+1.5\,M$), occur 10 or 15 times a year in the region $150\times150\times50\,km^3$ of the Japan Islands. Substituting the heat flow for energy of the above earthquakes, we get

2) J. VERHOOGEN, *Am. Journ. Sci.*, **244** (1946), 745.

3) C. TSUBOI, *Geophys. Notes* (*Geophys. Inst., Tokyo Univ.*), **3** (1949), No. 4; *Journ. Phys. Earth*, **5** (1957), 1.

$$\frac{10^{23}\,erg.}{150\times 150\,km^2\times 1\,yr.}=3.3\times 10^{-7}\,cal./cm^2\cdot sec. \qquad (2)$$

Recently, B. Gutenberg[4] discussed the energy of earthquake and stated as follows: *The average annual energy release of about 10^{25} ergs may be compared with an annual energy loss of the earth of nearly 10^{28} ergs by heat flowing out of the interior across the earth's surface. Thus, for the whole earth, the average heat developed during earthquakes is roughly one-thousandth of the heat flow through the surface; however, in earthquake zones locally both quantities may be of the same order of magnitude. Assuming a width of 250 km for the Japanese and Solomon Islands earthquake zones, the most active on earth, an average annual energy release of the order of magnitude 10^8 ergs/cm^2 ($\approx 10^{-7}$ cal./cm$^2\cdot$sec.) results for these zones, which is roughly one-tenth of the average energy released in radioactive heat in the earth. However, it has to be considered that the processes which produce the strain resulting ultimately in earthquakes may receive their energy from areas far beyond the earthquake belts. Thus, the energy of earthquakes could well result ultimately from radioactive processes in the earth's interior.*

E. C. Bullard[5], who deems the volcanic heat to be derived from the dissipation of mechanical energy associated with earthquakes, mentioned the following figures: Smoothed curve involving the epicenters of the shallow earthquakes in the Japan-Kamchatka area is found to have an area of $2.0\times 10^6\,km^2$ and the average energy sent out as seismic waves from this area is 1.7×10^{26} *ergs/year* (this value may be converted to about 10^{25} *ergs/year* by the new energy formula) both according to Gutenberg and Richter's book. Using the abovementioned figures, heat flow substituted for earthquakes is estimated as follows;

$$\frac{10^{25}\,erg./yr.}{2.0\times 10^6\,km^2}\approx 10^{-7}\,cal./cm^2\cdot sec. \qquad (3)$$

According to his assumption, the remainder of the elastic energy that gave rise to the earthquake is dissipated as heat near the focus and this energy may be at least as great as that appearing as seismic waves. Thus, energy that has been stored as elastic energy should be double the above figure.

Recently T. Matuzawa[6] formed a theory of earthquake field from

4) B. GUTENBERG, *Quart. Journ. Geol. Soc. London*, **112** (1956), 1.
5) E. C. BULLARD, in G. P. Kuiper (ed.), *The Earth as a Planet* (1954), 120.
6) T. MATUZAWA, *Bull. Earthq. Res. Inst.*, **31** (1953), 179.

the point of view that a solid-liquid phase transformation at the bottom of the crust may supply strain energy to the crust and cause a great earthquake to occur. Statistical studies show that a great earthquake having an energy of 10^{25} *ergs* occurs once a hundred *years* in the circular region of radius 50 *km* in the Japanese seismic zone. Matuzawa pointed out that heat of fusion amounting to about 9×10^{27} *ergs* should be supplied gradually from the deep into the bottom of the crust to give rise to the abovementioned earthquake as a result of the phase transformation. This supply of thermal energy for heat of fusion from the deep is equivalent to the following heat flow

$$\frac{9\times10^{27}\,erg}{100\,yr.\times\pi\times50^2\,km^2}=8.5\times10^{-4}\,cal./cm^2\cdot sec. \qquad (4)$$

3. Dissipation of energy in earthquake occurrences and volcanism.

As mentioned in the previous section, Tsuboi, Gutenberg and Bullard estimated the energy of seismic waves per unit area and unit time, while Matuzawa discussed quantitatively the mechanism and the supplied energy which should cause the great earthquakes to occur and concluded that the supply of thermal energy to the earthquake zone is about 800 times the normal heat flow observed at the earth-surface. Remainder of the elastic energy should be dissipated as heat.

If we use the term "Squander factor (*S* factor)" as the ratio of the dissipated energy to the various energies which we could observe, this factor amounts to about 10^2 in the case of the great earthquakes according to Matuzawa's analyses mentioned above.*

As regards volcanic activities, their occurrence is rare and their quantitative observations are rather difficult compared to those of earthquakes. Therefore, we have scarcely the statistical and quantitative methods by which we might estimate the supplied energy from the deep to the magma-reservoir except the geomagnetic method for basaltic volcanoes as discussed in the previous papers. By this method, the writer estimated the lowest amount of thermal energy supposed to be supplied to the magma-reservoir assuming that the changes in the geomagnetic field on the volcano should be caused by the rise of temperature in the reservoir. The order of magnitude of the squander factor for the two cases of activities on Volcano Mihara, 1950 and 1953 $\sim$ 54

*) The effective fuel efficiency of the usual steam-locomotive is about 10%, namely, its *S* factor equals 90/10=9.

are shown as follows;

for the 1950 eruption:

$$\frac{1.1\times10^{26}\,ergs}{9.4\times10^{23}\,ergs}=120\,,$$

for the 1953 ~ 54 eruption:

$$\frac{1.9\times10^{24}\,ergs}{1.3\times10^{22}\,ergs}=150\,.$$

4. Volcanic heat associated with the Seven Izu Islands.

Repetitions of volcanic eruption during long periods should have composed the mountain-mass of a volcano, especially of a stratified one. The largest part of the energy released from a volcano is the thermal energy accompanied by the essential lava flows (the A-type ejecta). Here, we may make a rough estimation of the total energy consumed by the formation of volcanoes assuming that their ejecta were all of the A-type.

The Seven Izu Islands are one branch of the festoon islands and run southward perpendicularly to Japan Proper (Honshu). This archipelago extends about 700 *km* and continues to Mariana Islands via Bonin (Ogasawara) Islands and Sulphur (Iwoo) Islands. All the islands are volcanic ones including active,

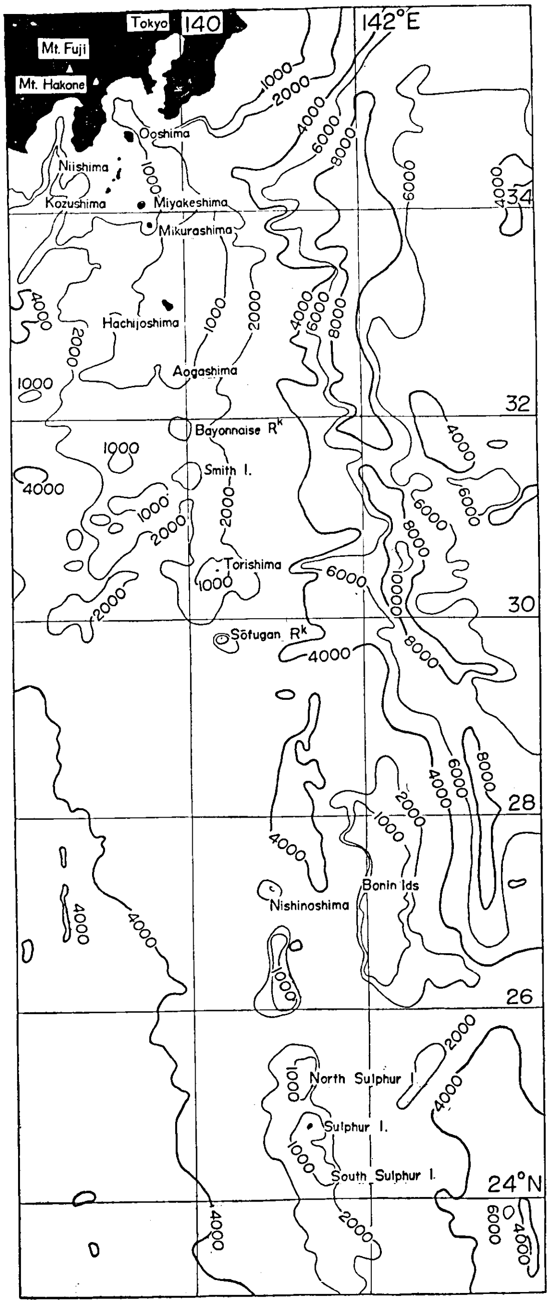

Fig. 1. The Seven Izu Islands (numerals show the depth of the sea in *meter*).

dormant and extinct Quaternary volcanoes except Bonin Islands which are Tertiary and form a volcanic zone together with Mts. Huji (Fuji) and Hakone in the mainland. It is remarkable that this volcanic zone is situated on the line of positive gravity-anomaly, while there is the line of negative anomaly along the Japan Trench eastward about 200 *km* from the islands and in the western side of the volcanic zone, epicentres of shallow and deep earthquakes are distributed on the plane westwardly dipping. The writer, here, will roughly estimate the total volcanic energy over the zone since its genesis.

First, the volume of the volcanic island is obtained by the topographic maps and bathygraphic charts assuming that the upheaval from the general slope of the sea-bottom around the island represents the region related to volcanic activities, whether the bottom meterial is volcanic ejecta or not. In fact, this upheaval would be caused by the intrusions of magma into the volcano which usually centres at the island. Furthermore, determination of the bottom-depth of the volcanic island does not seriously affect the results of the following order-estimation as shown in the example of Ooshima Island:

Volume above	sea-level	20 km^3
〃 〃	$-300\ m$	71 〃
〃 〃	$-500\ m$	140 〃

And effects of marine erosion on the volume of the islands may be neglected without serious error in our discussion. Volume and adopted bottom-depth of each island are shown in Table I where the four islands Toshima, Utoneshima, Niizima and Koozushima are remarkably small.

Thermal energy released by formation of the volcanic island is obtained by the equation (5) in 2nd Paper as

$$E_{th} = Volume \times 2.3\ gr./cc \times 300\ cal./gr. \times J \quad (ergs), \tag{5}$$

and shown in Table I.

The Seven Izu Islands are distributed on a belt about 50 *km* wide and form a volcanic zone. By the term "volcanic zone", we generally mean approximately uniform scattering of volcanoes on a belt. So, assuming that the larger a volcano is, the wider its energy-source will be, the writer defines the mean energy-density of one volcanic island as

$$\overline{E}_n = \frac{E_n}{\Delta x_n \dfrac{E_n}{E_{n-1}} + \Delta x_{n+1} \dfrac{E_n}{E_{n+1}}} . \tag{6}$$

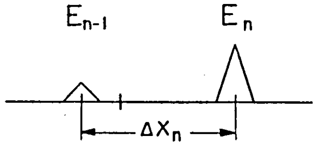

Fig. 2.

They are also shown in Table I and expressed in Fig. 3 where Soofu-gan Rocks and others to the south take rather small values. In the following discussion, the writer adopts the arithmetic mean value 4×10^{25} *ergs/km* as the linear density of volcanic energy for the region from Ooshima to Torishima.

The volcanoes in this zone developed their activities since the end

Table I. Volume of the Seven Izu Islands and Energy released by their formation.

Island	Latitude (North)	Bottom Depth (*m*)	Volume (*cc*)	Thermal Energy (*erg*)	Energy Density (*erg/km*)	Rocks
Ooshima	34° 45′	− 300	7.1×10^{16}	2.0×10^{27}	——	Basalt
Toshima	34 30	− 100	1.9×10^{15}	5.5×10^{25}	small	Basalt
Utoneshima	34 28	− 100	0.4×10^{15}	1.2×10^{25}	small	Basalt
Niizima (incl. Shikine I.)	34 22	− 100	1.0×10^{16}	3.0×10^{26}	small	Liparite
Koozushima	34 12	− 100	9.2×10^{15}	2.6×10^{26}	small	Liparite
Miyakeshima	34 05	− 300	5.8×10^{16}	1.7×10^{27}	3.6×10^{25}	Basalt
Mikurashima	33 52	−1000	9.7×10^{16}	2.8×10^{27}	4.6 〃	Basalt, Andesite
Hachizyoshima	33 05	− 500	4.0×10^{17}	1.2×10^{28}	1.6 〃	Basalt, Andesite
Aogashima	32 28	− 800	7.7×10^{16}	2.2×10^{27}	6.5 〃	Basalt, Andesite
Bayonese Rocks	31 55	−1200	2.2×10^{17}	6.3×10^{27}	3.0 〃	Basalt
Smith Island	31 24	−1200	3.0×10^{17}	8.6×10^{27}	7.6 〃	
Torishima	30 28	−1600	6.9×10^{17}	2.0×10^{28}	3.4 〃	Basalt, Andesite
Soofu-gan Rocks	29 50	−2000	1.6×10^{17}	4.6×10^{27}	0.4 〃	
Nishinoshima	27 14	−1000	4.4×10^{16}	1.3×10^{27}	1.1 〃	
North Sulphur Island	25 25	−1000	2.8×10^{17}	8.1×10^{27}	0.6 〃	Basalt
Sulphur I. (incl. South Sulphur I.)	24 45	−1000	8.8×10^{17}	2.5×10^{28}	——	Trachyandesite

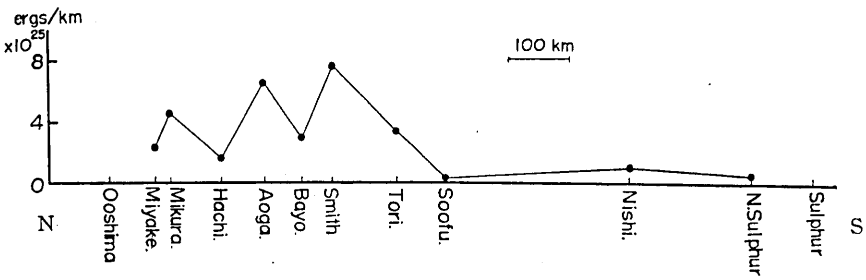

Fig. 3. Mean energy-density of the Seven Izu Islands.

of Tertiary or later period. Therefore, the rate of energy-release becomes as

$$\frac{4\times 10^{25}\,erg./\,km}{10^{6}\,yr.\times 50\,km}=6.0\times 10^{-8}\,cal./cm^{2}\cdot sec. \qquad (7)$$

The writer would rather say that real release of volcanic energy is to be obtained by multiplying the above value by an "S factor" which is estimated at 150 as has been discussed in the previous section. Then, we get the heat flow substituted for the total volcanic energy in the Seven Izu Islands as

$$9.0\times 10^{-6}\,cal./cm^{2}\cdot sec.$$

5. Conclusion.

Three investigators (Tsuboi, Gutenberg and Bullard) estimated the energy-release by earthquake-waves in Japan and the surrounding region as the order of $10^{-7}\,cal./cm^{2}\cdot sec.$ coincided with each other. Verhoogen discussed the igneous activities on the earth as a whole and obtained the value $10^{-10}\,cal./cm^{2}\cdot sec.$ In this paper volcanic energy released in "the volcanic zone" the Seven Izu Islands is estimated at $10^{-7}\,cal./cm^{2}\cdot sec.$ in net amount. It is clear and very plausible that the heat-flow has been more concentrated in the volcanic zone than in the other regions though the example is the only one for a volcanic zone in the ocean.

Matuzawa deduced theoretically the all-inclusive energy-release of earthquakes as the order of $10^{-3}\,cal./cm^{2}\cdot sec.$, while the volcanic one was obtained as the order of $10^{-5}\,cal./cm^{2}\cdot sec.$ in this paper. The former is conspicuously larger than the latter and both two are larger than the normal heat flow at the earth-surface, namely $10^{-6}\,cal./cm^{2}\cdot sec.$ This estimate may be taken as suggesting that the terrestrial heat flow is more or less focused in the seismic and volcanic zones. Regarding the general association of both two zones we can not compare them with each other adopting the above figures because we scarcely know how active the seismic zone was in the past. At the present stage the writer is not able to say positively that volcanism is a derivative of earthquakes and prefers to say that both are equally the derivatives of the same rank from the thermal energy contained in the bottom of the crust or the mantle.

In concluding, the writer wishes to express his sincerest thanks to Dr. T. Rikitake who advised him throughout the course of this study.

7. 火山活動のエネルギー (第3報)

地震研究所 横 山 泉

第1報，第2報で得られた結果を基として，いわゆる火山帯なるものの意義をエネルギー論から検討した．既に地震帯なるものについては，諸学者がいろいろな算定を行い，これからいろいろな説を立てているので，一応これを概観した．火山帯の例として，伊豆七島をとり，これが形成されるまでに放出されたであろう熱エネルギーの量を概算して，地震帯のエネルギーと比較吟味した．