14. *Energetics in Active Volcanoes. 1st Paper. (Activities of Volcano Mihara, Ooshima Island during the Period 1953~54)*

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1. Introduction.

T. Minakami[1] has been investigating the energy of volcanic eruptions and its relation to volcanic earthquakes. As a result of his twenty years' observation on Volcano Asama which is of typical *Vulcanian* type, it is established that the energy of a violent eruption amounts to the order of 10^{20} *ergs*, and that of a moderate one to 10^{18} *ergs*.

In order to understand volcanic phenomena more clearly, however, it is desirable to see how much energy is supplied to the volcano from below, and what percent of it is spent in carrying up welled lava, eruptions at the crater, volcanic tremors, earthquakes and so on. Although it is not possible to get at the complete energetics associated with volcanic activities until the physical and chemical mechanism existing in and under the volcano is made clear, the geomagnetic studies on Volcano Mihara which is typically *Strombolian*, enable us to attempt energetics in active volcanoes because studies giving some clue to the incoming energy have been published by the writer[2].

Here, the writer is going to summarize the quantitative data accumulated by geomagnetic and seismological methods on Volcano Mihara, Ooshima Island in 1953 and 1954 during which period we observed moderate activities. We have obtained many sorts of data which are useful for studying energetics associated with the activities. At the surface of the volcano, first of all, we have observed volcanic tremors which are closely related to the surface activities and also local earthquakes which may be associated with the release of energy in the deep interior of the volcano. With the aid of geomagnetic observations, some knowledge of the depth and thermal state of the magma-reservoir

1) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **20** (1942), 431.
2) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **34** (1956), 21.

under the volcano was also obtained. Furthermore, we could observe that the lava which newly overflowed had done the work against gravity and carried the thermal energy up to the earth-surface. However, no accurate estimate of the chemical energy below the volcano has been possible. It is also difficult to estimate the thermodynamical energy accompanied by the emission of water-vapour in the crater because of the difficulties in actual observations.

The purpose of this paper is to obtain the amounts of various energies as accurately as possible; therefore, no definite interpretation of the relation between energies of various types will be attempted here.

2. Energy of volcanic tremors.

The energy of volcanic tremors on Volcano Mihara during the period 1953~54, is estimated from the seismometrical records which are published in the Monthly Report on Activity of Volcano Mihara by the Ooshima Weather Station which is situated at a distance of 4.8 *km* from the crater. In this report we find the number of tremors per every six hours, the four largest of which are itemized into maximum amplitude, period and duration for every component. In order to deduce the total energy per day from the aforesaid 16 typical tremors, the writer made several assumptions and simplifications.

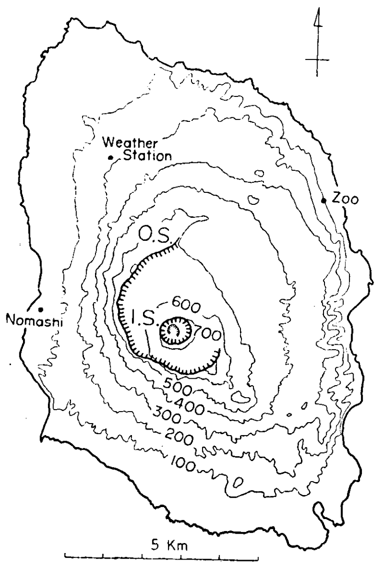

Fig. 1. Topographical map of Ooshima Island.
I.S.: Inner somma
O.S.: Outer somma

As a character common to the explosive activities of *Strombolian* type volcanoes, explosion earthquakes, accompanied by each individual explosive eruption at short intervals of a few *seconds*, appear as continuous waves of the pulsation type. The amplitude of seismic waves of the continuous tremors prospers and decays with changes in the intensity of explosion. So we can not find a definite relation between the maximum amplitude and duration time. The writer, here, assumes for brevity that every wave has the same amplitude, namely maximum amplitude, during its duration.

To check the relation between four sets of the four largest tremors and the total number in a whole day, here we pick out two days, one is minor and another major in number. Frequency of occurrence of tremors for maximum double amplitude of N-S component on Dec. 6, 1953 and Feb. 6, 1954 are shown in Fig. 2. The mean values of the 16 tremors are 7.5μ and 11.0μ respectively. The modes of distribution in the figure are similar to that obtained by S. Murauchi[3] at Volcano Suwanose-zima in Tokara Islands belonging to the Riu-Kiu Volcanic Belt.

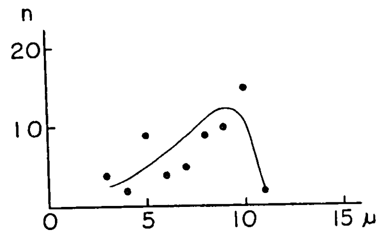

Fig. 2 (a).

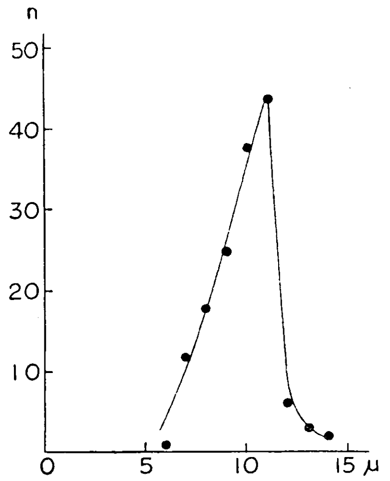

Fig. 2 (b).

Fig. 2. Occurrence-frequency of maximum double amplitude (NS component). (a) Dec. 6, 1953. (b) Feb. 6, 1954.

As proved by T. Minakami[4], the tremor on Volcano Mihara has the character of surface waves, so that the estimate of energy of the tremor will be made by K. E. Bullen's method[5] for surface waves. Though the actual mode of vibrations seems very complicated, we assume for the sake of convenience that the tremor has the character of the Rayleigh type. The order of magnitude-estimate of the energy is not likely to be affected seriously by this assumption.

The components of the displacement of the earth movement during the passage of a group of Rayleigh waves are given by

$$\left.\begin{aligned} u&=a\{\exp(0.85\kappa z)\\ &\quad-0.58\exp(0.39\kappa z)\}\\ &\quad\times\sin\{\kappa(x-ct)\}\\ w&=a\{-0.85\exp(0.85\kappa z)\\ &\quad+1.47\exp(0.39\kappa z)\}\\ &\quad\times\cos\{\kappa(x-ct)\} \end{aligned}\right\}, \qquad (1)$$

where a is a constant determining the amplitude, $2\pi/\kappa$ is the wave-length, c is the wave velocity, and $z=0$ is taken as the equation of

3) S. MURAUCHI, *Bull. Nation. Sci. Museum (Tokyo)*, **1** (1954), 13.

4) T. MINAKAMI, T. MIYAZAKI and T. TAKAHASHI, *Bull. Earthq. Res. Inst.*, **29** (1951), 359.

5) K. E. BULLEN, *An Introduction to the Theory of Seismology* (1947), p. 231.

the earth's outer surface. u and w indicate components parallel to the direction of propagation of the waves and vertically upwards, respectively. Putting z equal to zero, we get

$$\left.\begin{aligned} u&=0.42a\sin\{\kappa(x-ct)\} \\ w&=0.62a\cos\{\kappa(x-ct)\} \end{aligned}\right\} . \tag{2}$$

The components of velocity are given by

$$\left.\begin{aligned} \dot{u}&=a\kappa c\{-\exp(0.85\kappa z)+0.58\exp(0.39\kappa z)\}\cos\{\kappa(x-ct)\} \\ \dot{w}&=a\kappa c\{-0.85\exp(0.85\kappa z)+1.47\exp(0.39\kappa z)\}\sin\{\kappa(x-ct)\} \end{aligned}\right\} . \tag{3}$$

The mean kinetic energy per unit volume is $1/2\rho$ times the mean value over one wave-length of $(\dot{u}^2+\dot{w}^2)$, namely

$$\frac{1}{\tau}\int_0^\tau(\dot{u}^2+\dot{w}^2)dt=a^2\kappa^2c^2\{0.86\exp(1.70\kappa z)-1.82\exp(1.24\kappa z) \\ +1.24\exp(0.78\kappa z)\} . \tag{4}$$

The total mean energy per unit volume is double this. Integrating this result over the range $0\geqq z\geqq-\infty$, we get the total energy per unit earth surface area as follows.

$$\rho a^2\kappa^2c^2\int_0^\infty\{0.86\exp(1.70\kappa z)-1.82\exp(1.24\kappa z)+1.24\exp(0.78\kappa z)\}dz \\ =0.63\rho a^2\kappa^2c^2=1.26\pi\rho a^2\lambda\tau^{-2} . \tag{5}$$

The order of energy in the Rayleigh waves which pass across the cylinder of radius r centred at the epicentre will be given by

$$2.5\pi^2\rho r\int ca^2\lambda\tau^{-2}dt . \tag{6}$$

According to T. Hirono[6], the energy of an earthquake which is caused by vertical impulses at the ground surface is equally divided into solid waves and Rayleigh waves. So, total energy of the earthquake is double the expression (6), namely

$$E=5.0\pi^2\rho r\int ca^2\lambda\tau^{-2}dt . \tag{7}$$

If we put the amplitude of the horizontal component of the surface motion in Rayleigh waves as A, we obtain from (2)

$$A=0.42a . \tag{8}$$

6) T. HIRONO, *Geophys. Mag.*, **18** (1949), 102.

Instead of using all tremors, we make use of the 16 typical ones assuming that total energy per day is proportional to the total number of tremors and so (7) is converted to

$$E=5.0\pi^2\rho r\frac{c^2}{0.42^2}\frac{n}{16}\sum_1^{16}A^2\frac{\Delta T}{\tau} \qquad (9)$$

where r is 4.8 km and A, ΔT, τ and n are observable. For the sake of convenience the following assumptions are adopted: density $\rho=2.0\, gr/cc$ and wave velocity $c=10^3\, m/sec$. We obtain finally

$$E=2.68\times\frac{n}{16}\times10^{10}\sum A^2\frac{\Delta T}{\tau}\ (erg)\ , \qquad (10)$$

where A is measured in *micron*. The approximate summation is rather successful as shown by the following examples where the daily energy is obtained from only the N-S component. The results thus obtained

Date	Total number of tremors	Energy obtained by eq. (10)	
		Using 16 tremors	Using all tremors
Dec. 6, 1953	60	3.9×10^{16} *ergs*	4.0×10^{16} *ergs*
Feb. 6, 1954	149	5.2×10^{16}	5.8×10^{16}

are shown by the column for each day in Fig. 3. Energy lower than 10^{10} *ergs* is marked at the bottom of the figure. Of course, these results may be unavoidably uncertain by a factor of at least ten.

It is natural that the increase and decrease of daily energy of volcanic tremors correspond closely to those of the surface volcanic activities, because the sources of the tremors would be at a part of the volcanic vent not far from the surface.

3. Energy of volcanic earthquakes.

In estimating the energy of local shocks associated with volcanic activities in Ooshima Island, the Seismological Bulletin of the Central Meteorol. Observatory, Japan is available. Various constants of the seismographs of the Ooshima Weather Station are shown in Table I. Felt and unfelt shocks are listed in Tables II and III according to the above Bulletin.

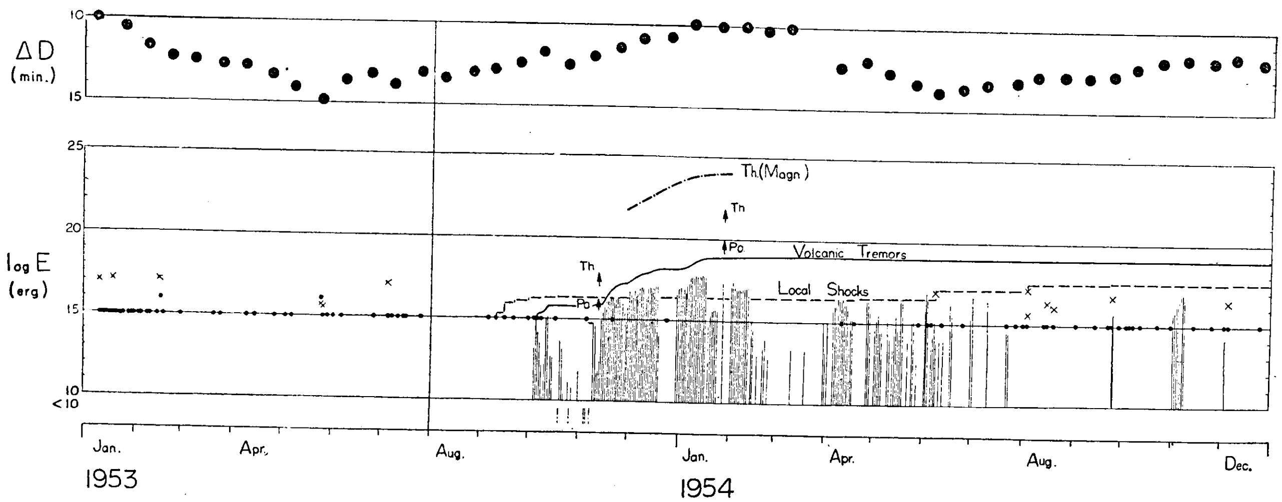

Fig. 3. Release of volcanic energies at Volcano Mihara.

● Changes in semi-monthly means of the westerly declination.
× 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 energy of volcanic tremors since August, 1953.
- - - Integrated energy of local shocks 〃 .

Table I. Constants of seismographs at the Ooshima Weather Station. (May 20, 1954)

The Wiehert type	Magnification V	Period T_0	Damping ratio v
N—S	100	5.0 sec.	7
E—W	99	4.9	7
U—D	67	4.9	8

Table II. Daily numbers of unfelt and felt local shocks (after the Ooshima Weather Station).

Month \ Date	1~10	11~20	21~	Month \ Date	1~10	11~20	21~
1953				1954			
Jan.	3	1,1,1,1,1,5,4	1,1,6,1,2	Jan.	—	—	—
Feb.	2,2,2,2	1,8.3	1	Feb.	—	—	—
Mar.	—	1	1	Mar.	—	—	—
Apr.	2	1	1	Apr.	1	1	—
May	1,1	—	17,4,2	May	—	—	1
June	1,3	—	2	June	4,1,1	1	3
July	2,1	1,1,1,	1	July	—	—	1,1
Aug.	—	—	—	Aug.	1,2	1,1,3	—
Sept.	1,1	7	3,5	Sept.	2	—	2,4,1
Oct.	1,1,1	2	—	Oct.	1,1,1	1	3,1
Nov.	1	—	1	Nov.	—	1	3
Dec.	—	—	1	Dec.	2,2	—	1

After B. Gutenberg and C. F. Richter[7], the energy of earthquake E is connected with the instrumental magnitude M by

$$\log E = 11.8 + 1.5M \tag{11}$$

where M is defined as the common logarithm of maximum trace amplitude expressed in *micron* with which the standard Wood-Anderson torsion seismometer (period $T=0.8\,sec.$, magnification $V=2800$, damping $h=0.8$) would register that earthquake at the epicentral distance of 100 *km*. For determining the instrumental magnitude M, C. Tsuboi[8] obtained formulas by consideration of only those earthquakes which had occurred in and near Japan and had been observed in Japan. But his

7) B. GUTENBERG and C. F. RICHTER, *Bull. Seism. Soc. Amer.*, **32** (1942), 163. The revised formula was communicated by Prof. C. Tsuboi who came back lately from U.S.A.

8) C. TSUBOI, *Geophys. Notes, Geophys. Inst., Tokyo Univ.*, **4**, No. 5.

Table III. Principal local shocks observed at the Ooshima Weather Station.

P (J.S.T.)			Intensity	$P\sim S$	$P\sim F$	Δ	A	M	$\log E$
		d h m		sec	m s	km	μ		
1953	Jan.	10 07 31	I	2.1	—	14.7	52.9	3.50	17.0
		19 11 35	I	2.4	1 11	16.8	41.7	3.51	17.1
	Feb.	16 15 27	II	1.8	1 14	12.6	80.0	3.54	17.1
	May	26 18 36	0	1.1	54	7·7	21.6	2.54	15.6
		27 02 18	0	1.1	1 05	7.7	19.0	2.49	15.5
	July	5 12 45	I	1.6	1 36	11.2	84.9	3.46	17.0
1954	June	8 23 49	I	2.7	1 07	18.9	25.4	3.40	16.9
		3 07 09	I	0.9	35	6.3	33.4	2.56	15.6
		3 12 42	I	2.5	1 15	17.5	43.3	3.56	17.1
		14 13 49	0	—	55	(12.6)	21.4	2.97	16.3
		19 21 57	0	—	35	(12.6)	14.1	2.79	16.0
	Sept.	24 16 25	II	1.9	1 30	13.3	35.6	3.24	16.7
	Dec.	5 01 05	0	—	1 30	(12.6)	28.6	3.10	16.4
		*5 01 11	0	—	30	(12.6)	$1\sim2$	1.94	14.7

* An example of unfelt shocks.

formulas are concerned with those earthquakes larger than damaging ones, in other words, $M \geqq 5$. On the other hand, Gutenberg and Richter defined the energy of an earthquake of zero magnitude as 10^{12} *ergs*. Therefore, we apply the Gutenberg and Richter's method to the estimate of the energy of volcanic earthquakes under Volcano Mihara.

Taking into consideration the fact that the period about the maximum amplitude of the local shocks on Volcano Mihara is $0.1\sim0.2$ *sec.*, we make correction for the dynamic magnification and then obtain M for each shock. By eq. (11), the energy of earthquake is estimated as shown in Table III and Fig. 3. Many unfelt earthquakes were observed, of which amplitudes were $1\sim2\,\mu$. Smaller earthquakes than these are not detectable in the seismograms. Energy of an unfelt shock is shown in Table III as an example. Thus, we estimate the average energy released in an unfelt shock at the order of 10^{15} *ergs*. In Fig. 3, small circles representing unfelt shocks are marked on the line of 10^{15} *ergs*.

4. Energy released in other forms.

Eenergy is released in different ways from a volcano at the time of an eruption, namely as volcanic tremors, local shocks of volcanic origin, and ejection of lavas or vapours.

As already reported in the Bulletin[9], thermal energy, that is needed for heating the lava-reservoir and resulting in changes in geomagnetic declination of about 4 *minutes* of arc as observed at Nomashi, was estimated at about 4.5×10^{16} *cal.* (1.9×10^{24} *ergs*), so that we see that the amount of energy released from the Mihara crater during a period of 5 months since Aug., 1953 should be the same or a little greater than the figure cited above.

During the period of these activities, overflowing of fluidal lava was observed twice, though we have no complete knowledge of the processes which occurred beneath the earth's surface. The welled lava had done some work against gravity, while some heat was carried up to the surface with the lava mass. As a result of the analysis of anomalous changes in the geomagnetic field during the period, the writer[10] concluded that the depth of the magma-reservoir was about 2 *km*. Considering that the temperature of molten lava was about 1000°*C* at the crater, two cases are described as follows.

Nov. 12, 1953 ($6\times10^{2}\,m^3$)	Potential energy	2.4×10^{16} *ergs*
	Thermal 〃	8.1×10^{17} 〃
Jan. 27, 1954 ($4\times10^{5}\,m^3$)	Potential energy	1.6×10^{20} *ergs*
	Thermal 〃	6.7×10^{22} 〃

In addition to the above-mentioned activities, ejection of gas (mainly composed of water-vapour), paroxysmal activity at the crater and the chemical reactions under the volcano would play important roles in release of volcanic energy. But, unfortunately, we have had few quantitative observations on volcanoes for estimating the consumption of the thermal and kinetic energy by these various activities.

5. Discussion and summary.

Various energies concerning volcanic activities of Volcano Mihara in this period were estimated in the previous sections as shown in Fig. 3. Judging from the seismometrical and geomagnetic data, the activity beneath the volcano probably had begun already in the August, 1953, though the summit eruptions were recognized at first on Oct. 5 of the same year. Tentatively, we integrate the energies of tremors and local shocks since the August as shown in Fig. 3.

As will be seen in Fig. 3, local earthquakes generally do not occur

9), 10) I. YOKOYAMA, *loc. cit.*, 2).

simultaneously with volcanic tremors and the two are almost the same in their total energy. These facts suggest that the energy-sources of both tremors and shocks are the same and one of the differences between them is the place where they are released. It is, also, noticeable that the seismic energy on Volcano Mihara is almost comparable to that on Volcano Asama in its order if we integrate it through a period of activity though the energy of an individual *Vulcanian* explosion amounts 10^2 or 10^3 times that of a *Strombolian*.

Next, we are going to check whether income and release of the energies correspond each other or not. For an example, we select the

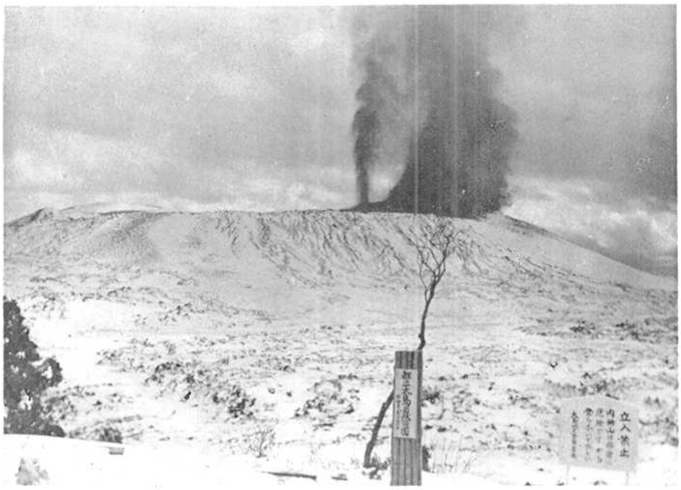

Fig. 4. Explosive eruption, Jan. 27, 1954, as seen from the outer somma, showing continuous spouting of molten lava.
Photo. by S. Watanabe.

eruption on Jan. 27, 1954. On this day, strong explosions occurred from $11\,h\ 20\,m$ to $16\,h\ 30\,m$ and smoke and fragments of lava were emitted as high as about $1000\,m$. During these $5\,hours$, about $4\times10^5\,m^3$ of molten lava overflowed into the crater like a fountain. The relation between each kind of energy on Jan. 27 is shown in Fig. 3. The thermal energy which had income into the magma-reservoir from below amounted to about $10^{24}\,ergs$ till January, 1954 as cited before (Th. Magn.). As for this incoming stage, we had no observed data to confer except the anomalous changes in geomagnetic declination as shown in the figure. The thermal energy released by the molten lava which overflowed into the crater in $5\,hours$ amounted to about $10^{22}\,ergs$ (Th.). The potential energy accompanied by the overflowed lava reached about 10^{20} *ergs* (Po.). And the seismic energy of volcanic tremors totaled 10^{17} *ergs*. Besides the above-mentioned phenomena, there might be release of energy by ejection of water-vapour and paroxysmal activity, and these seemed to play the most prominent role in release of energy in the following period as was fully discussed in the previous paper[11]. It is noticeable that efficiency of volcano as a heat-engine is very low.

Further discussion will be undertaken in later reports, adding other examples of Volcano Mihara or other volcanoes.

In conclusion, the author wishes to express his sincere thanks to Dr. T. Rikitake who offered him valuable suggestions in the course of this study. His sincere thanks are also due to the members of the Ooshima Weather Station who placed valuable data at his disposal.

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14. 火山活動のエネルギー (第 1 報)
(大島三原山の 1953～54 年間の活動について)

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大島における地磁気変化の連続観測結果を解析することによつて，その原因は火山の下にあり，この活動に際して，マグマ溜に補給された熱エネルギーは 10^{24} エルグと求められた．そしてこの間に放出されたエネルギーは，火山性脈動として 10^{19} エルグ，火山性局発地震として 10^{17} エルグ，地表において観察されただけの噴出熔岩について，その位置のエネルギーは 10^{20} エルグ，放出した熱エネルギーは 10^{22} エルグとなる．以上は大体の見積りではあるが，三原山のようなストロンボリ型噴火をする火山においても，その活動エネルギーは小さいものでないことを示すようである．

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11) I. YOKOYAMA, *loc. cit.*, 2).