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Prediction of Development in the 1977~78 Activities of Usu Volcano with Consideration for Energy Discharge

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Abstract

Prediction of the future development, rise and fall, in volcanic activities is not less important than that of the first outburst of eruptions. As in the usual case of dacite volcanisms, the activities of Usu Volcano in Hokkaido would continue persistently for rather long period. The present eruptions occurred at the summit crater. About the historical summit eruptions, we have not any instrumental observational data which might enable us to predict future development in the activities of the volcano. After the outbreak of the eruption, we have accumulated observational data by seismometric and geodetic methods. Analyzing the results obtained for the earlier six months, we arrived at a preliminary conclusion that both the discharge rate of seismic energy and the upheaval rate of new cryptodomes at the summit would decay exponentially with time. This means that the energy source beneath the volcano has been isolated from the depths; it would continue to decay exponentially with time unless it receives new supply of energy from the depths. Adopting the above preliminary conclusion for a certain period, we might predict the total seismic energy which is to be released by volcanic earthquakes and the final heights which are to be achieved by the new cryptodomes, both by the end of the present activities. However, both the modes of the discharge rate of seismic energy and the upheaval rate changed after October 1978 when the eruptions in the summit crater stopped. Thereafter, both the rates have been small but almost constant with some fluctuations, and have not shown any conspicuous decay (up to October 1979). In order to interpret these peculiar activities, it is necessary to accumulate the observational data for longer period.

1. Introduction

Usu Volcano in southern Hokkaido is about 700 m high a.s.l. and about 6 km in diameter at the base, and has a summit crater of which diameter is about 2 km.

Historically it early repeated summit eruptions four times (1663, 1769, 1822 and 1853) forming two lava domes (Ko-Usu and Oo-Usu) in the summit crater, and thereafter ouburst at the foot forming Meiji-Shinzan (cryptodome)

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in 1910 and Showa-Shinzan (lava dome) in 1943~45. All the domes are dacitic while the somma lava is basaltic. The 1910 eruption and the 1943~45 eruption were fully observed and adequately discussed at the highest level of earth-sciences of these epochs by Omori[1] and Minakami et al.[2] respectively.
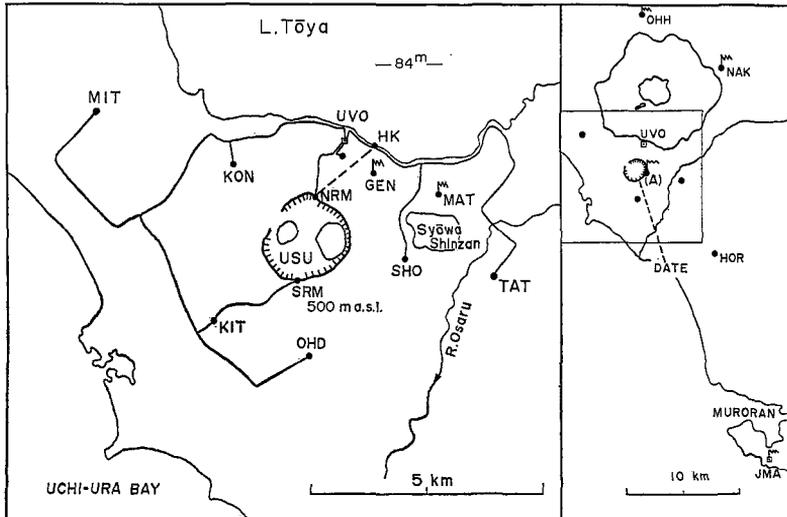

Fig. 1   Usu Volcano and the surrounding seismometric networks.

Usu Volcano broke out into the eruption at the summit on Aug. 7, 1977 after a 32 years' quiescence. During the first week, it ejected about $3 \times 10^7 \, m^3$ of pumice, ash and rock fragments forming 4 explosion craters (Craters 1~4 in Fig. 2), and caused large disasters at the towns around it. The sequence of the early stage of the 1977 eruption was throughly reported by Katsui et al.[3] The activities have been continuously accompanied by earthquake swarms and ground deformations. In November 1977, the first steam explosion occurred forming Crater A. It was followed by Crater B in Jaunary 1978, Craters C and D in February, Craters E, F, G and H in March, and Crater I in April. Crater I was very active for more than two months ejecting ash violently, and after June 1978 a part of the crater has been red hot (up to October 1979). In July 1978 Craters J, K and L were formed by ash eruptions, and in August these craters were agglomerated into a large one including Crater M formed in August. This large crater, "Gin-numa Crater" repeated ash eruptions for August and September, and sometimes hurled out incandescent

essential fragments (on Aug. 16, Aug. 24 and Sep. 12).   The last craterlet N was formed with small activity in October 1978.   Thereafter no eruptions have occurred, but volcanic earthquakes and ground deformations are still going on (up to October 1979) although they are about one twentieth of their highest activities in 1977.

The original data of volcanological observations of the 1977–78 eruption of Usu Volcano are preliminarily presented on the Report of the Coordinating Committee for Prediction of Volcanic Eruptions (No. 11~) in Japanese.
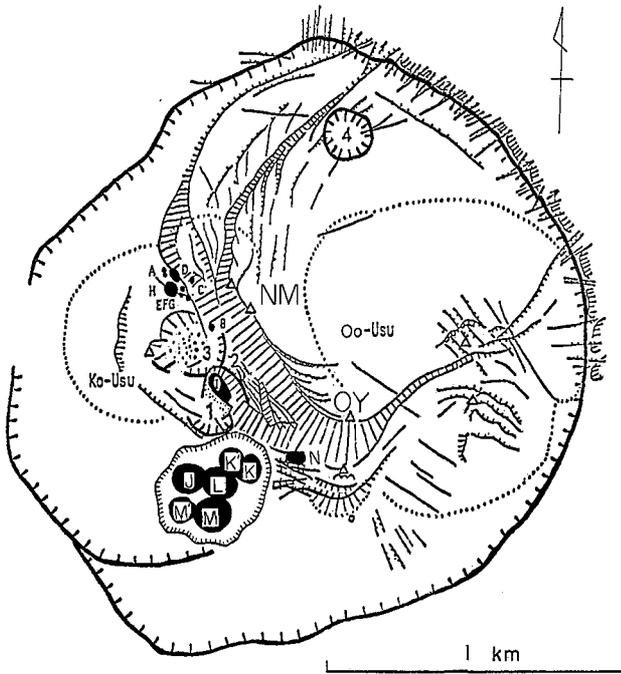

Fig. 2   Topographic sketch map of the summit crater of Usu Volcano as of Oct. 1978 (after Y. Katsui et al.).

2.   Observation of seismic activities

Before the 1977~78 eruption, there was a routine seismometric station equipped with 3 component transducers on the eastern somma (Point A in Fig. 1) and it transmitted signals by radio to the Muroran Local Meteorological Observatory, JMA about 25 km distant from the volcano.   In the early morning of Aug. 6, 1978, earthquake swarms including felt shocks began to

occur.   Immediately 3 seismometric parties of the JMA and the Hokkaido
University were distributed around the volcano and supplemented the
routine observation.   They determined the epicenters roughly at the summit
region and the JMA often alerted the public about the crisis of eruptions.
The volcano outburst at $09^h 12^m$ on Aug. 7 without any victims.   The
forerunning shocks amounted at about 3,000 in number, including about 1,000
felt shocks.

Immediately after the outburst, telemeterized seismometric networks
were established on and around the volcano and all were concentrated at the
newly organized Usu Volcano Observatory (UVO) of the Hokkaido University
as shown in Fig. 1.

The results of seismometric observations by the above networks and their
interpretations will appear anywhere.   In this report, only some examples
of the epicenter distributions are given in Fig. 3 where the last topographies
shown in (c) are approximately similar to the present ones (up to October
1979).   The accuracy of the epicenter determinations is within in a few tens of
meters.   The volcanic earthquakes originating from Usu Volcano would mainly
cluster around the fault zone within the summit crater.   The upper depths of
the hypocenters located in the western part of the summit crater have shallowed
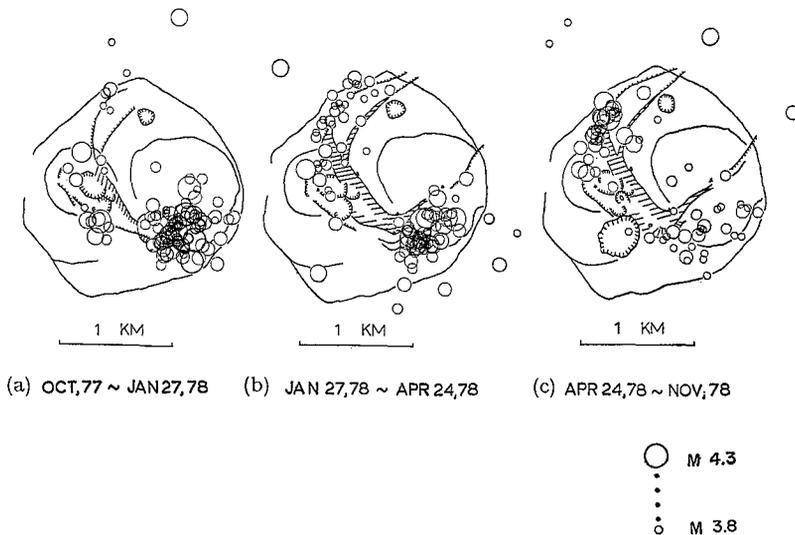

(a) OCT,77 ~ JAN27,78   (b) JAN 27,78 ~ APR 24,78   (c) APR 24,78 ~ NOV, 78

○ M 4.3
•
•
•
○ M 3.8

Fig. 3   Distributions of epicenters of volcanic earthquakes (M≥3.8) determined
for the period Oct. 1977 to Nov. 1978 (after Hm. Okada et al.).

gradually from about 300 m b.s.l. to about 200 m a.s.l. during these periods.

The seismic wave energies released by volcanic earthquakes originating from Usu Volcano are estimated by the amplitudes of surface waves observed by the Sapporo District Meteorological Observatory, JMA in Sapporo, about 70 km distant from the volcano. The magnitudes M of the earthquakes are determined by the total horizontal amplitudes $A(\mu)$ as follows:

$$M = \log A + 1.73 \log \Delta - 0.83 ,\tag{1}$$

where Δ is epicentral distance in km. And the energy E (erg) is estimated by

$$\log E = 1.5M + 11.8 .\tag{2}$$

The seismic energies of volcanic earthquakes of which amplitudes are larger than 5 μ at Sapporo, are all estimsted by the above formulas and represented as daily discharges in Fig. 4. In the figure, the accumulated sum is also shown and that as of September 1979 amounts to 8.5×10^{20} erg corresponding to an earthquake smaller than M 6.1.

The magnitude of the volcanic earthquakes has been limited to smaller than 4.3. The earthquakes of magnitude 4.3 were counted 20 up to October 1979.
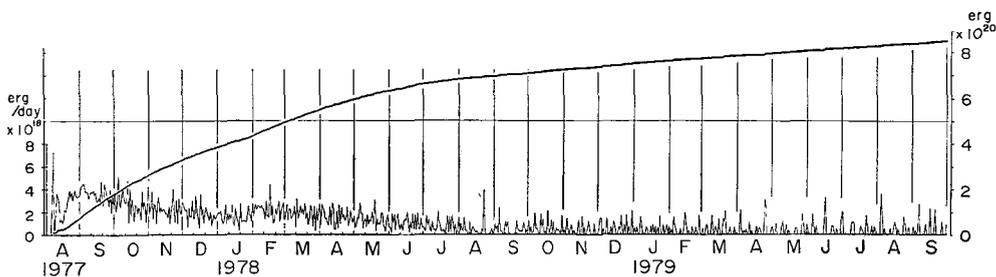

Fig. 4 Daily discharge of seismic energy and the accumulated sum.

3. Observation of deformation activities

A week after the outburst, an arch-shaped fault connecting the top of Oo-Usu lava dome and the eastern foot of Ko-Usu lava dome was recognized, and the north-eastern side of the fault upheaved day after day, about 1 meter per day at its maximum. Instrumental measurements of domings of a small hill, "Ogariyama" (growing mountain) in the summit crater by a theodolite from a distance of about 8 km south of the volcano were commenced 2 weeks after the outburst. At that time "New-mountain" at the east of Ko-Usu dome was not visible behind the somma rim, but cleared over the

rim on Sep. 27, 1977. Thereafter the targets of the measurements have been
two, Ogariyama (OY) and "New-mountain" (NM). These two targets have
shifted towards the north-east in the horizontal plane simultaneously with
the upward doming as shown later. In calculations of their upheavals, the
extension of the base lines are taken into consideration. The variations of
their heights above the sea level are shown in Fig. 5, where their original heights
before the eruption were 487 m (OY) and 488 m (NM). Both the domings
are almost parallel with each other. This means that the origin of both
the domings should be common and large in dimension.
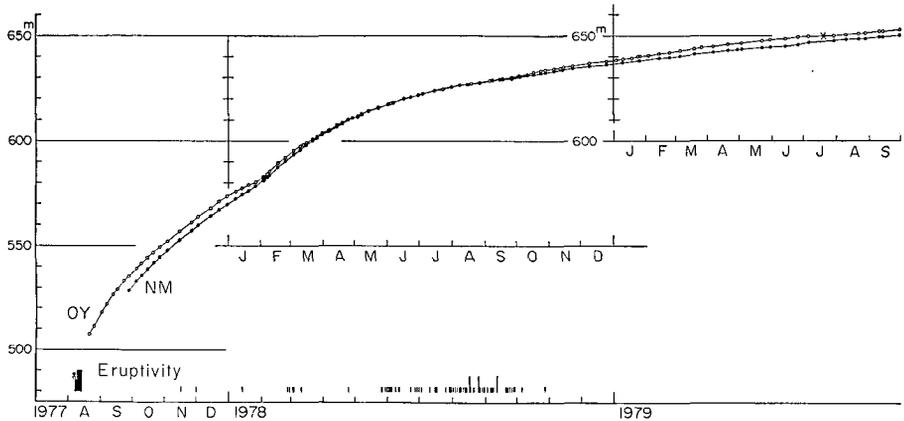

Fig. 5 Upheavals of the cryptodomes.
OY: Ogariyama, NM: New-mountain
A cross denotes a small collapse of the summit part of Ogariyama.

These domings midst of the summit crater unexpectedly caused the
northward thrust of its north-eastern quadrant, and consequently remarkable
ground deformations at the foot of the volcano. The full details will be left
to the other reports. In this paper, only the north-eastern thrust of the
crater rim is shown in Fig. 6 as an example. The measurement of the distance
between NRM and HK (Fig. 1) has been frequently repeated by a Geodimeter.
It contracted about 160 m since the outburst in 1977 up to October 1979.
And during the period, point HK has moved toward the north about 9.4 m
with reference to an island midst of Lake Toya.

For the purpose of examining the relation between occurrence of volcanic
earthquakes and that of deformations, the measurement of the northward

displacements of the northern somma is preferable to that of the upheavals of the domes because the former is more precise.   Harada et al.[4] carried out qasui-continuous Geodimeter measurements of the length of base line NRM-HK (about 1740 m) shown in Fig. 1 for about 40 hours on Dec. 7 and 8, 1978. It was found that the northward displacement is not always continuous but sometimes occurs intermittently, triggered by larger earthquakes, e.g. a sudden contraction of about 4 cm was observed simultaneously with an earthquake of M 3.9.
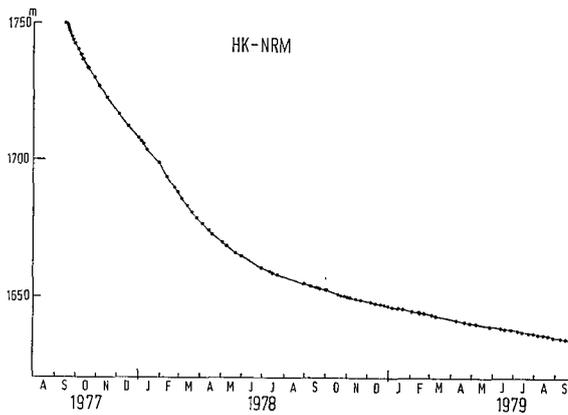
Fig. 6   Contraction of the base line between the lake shore and the northern rim of the summit crater, observed by a Geodimeter (after H. Watanabe et al.).

4. Energetic consideration

Variations of the daily discharge of seismic energy and of the daily rate of upheaval of Ogariyama are shown in Fig. 7 where they are clearly parallel to each other.

The energy necessary for the upheavals can not be estimated explicitly. The parallelism between the above two curves suggests that the upheaval rates are proportional to the upheaval energy which may be expressed as (variable upward displacement) × (constant total pressure).   And the parallelism also convinces us of that the seismic activities and the ground deformations on Usu Volcano have a unique and common energy source.

In Fig. 7, the variations of discharge of seismic energy are divided into Eruption Stage, 1st Stage and 2nd Stage, the latter two being bounded by a discontinuity at the end of January 1978 while the variations of rate of

upheaval lack in Eruption Stage because the observation of upheavals was begun after the earlier eruptions. The above discontinuity is also recognizable in the variations of northward thrust of the northern somma shown in Fig. 6. Eurption Stage in discharge of seismic energy is characterized by violent eruptivities and fluctuating seismic activities, and continued to the beginning of September 1977 when the eruptivities stopped and seismic activities and deformations began to predominate.
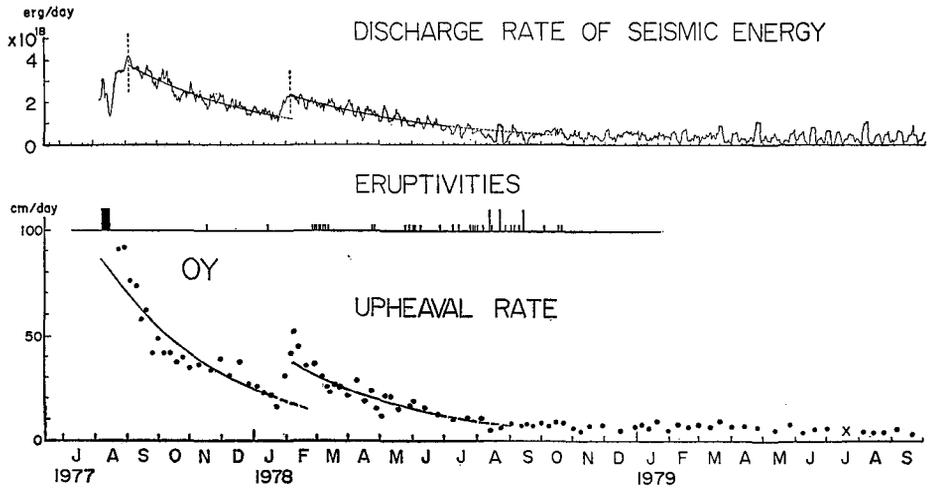

Fig. 7   Daily discharge rate of seismic energy averaged for every 5 days and daily upheaval rate of Ogariyama. A cross denotes a small collapse of the summit part of Ogariyama.

Both the curves at 1st Stage may be approximated by exponential curves as follows:

$$U_1 = 3.8 \times 10^{18}\, e^{-0.0072t} \qquad (\text{erg/day}) , \tag{3}$$

$$V_1 = 86.9\, e^{-0.0080t} \qquad (\text{cm/day}) , \tag{4}$$

where t is counted in days.

These facts may suggest that their common energy source beneath the volcano was isolated from the depths during 1st Stage; it would continue to decay exponentially with time if it does not receive any supply of energy from the depths. In fact, a small amount of energy may have been supplied, and this resulted in activation of discharge of seismic energy and upheavals at the end of January 1978 as shown in Fig. 7. Then we suspected new erup-

tions, probably even *nuée ardente* if the worst happened; fortunately nothing happened, and the increased activities again began to decay in the same manner as before.

The three larger explosions in August and September 1978 afford us important measures in estimating energy balance among volcanic activities such as explosions, earthquakes and deformations. As shown in Fig. 8, immediately after the three explosions which all hurled out some incandescent rocks from the Gin-numa Crater, the seismic activities stopped dead for a few days or a week.   We can estimate the energy of the explosions by knowing initial velocity and total mass of ejecta, and the deficiency of seismic energy for the days following   the explosions in Fig. 8.
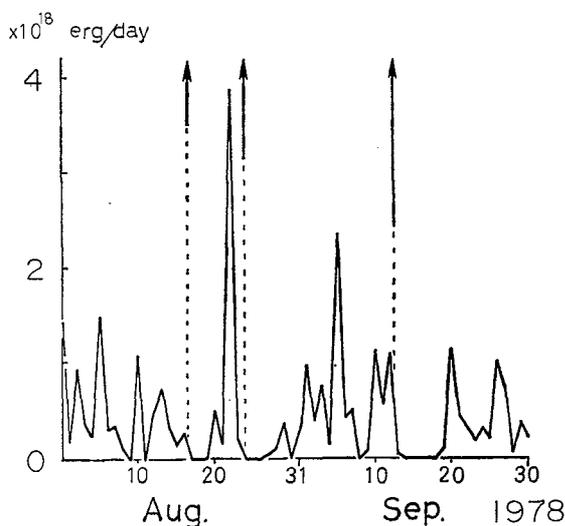

Fig. 8   Deficiencies of discharge of seismic energy for a few days immediately after the larger eruptions (indicated by arrows).   This is an enlargement of a part of Fig. 4.

Here, the case of the explosion on Sep. 12∼13, 1978 will be exemplified: Volume of the ejecta is approximately equal to that of the crater newly formed by the explosion and estimated as 5×10^{11} cc.   Taking the density original depth and initial velocity of the ejecta as 2 g/cc, 300 m and 80 m/s respectively, we may estimate kinetic and potential energies as 3.2×10^{19} erg and 1.0×10^{19} erg respectively.   Thus the total energy of the explosion becomes 4.2×10^{19} erg.   On the other hand, the deficiency of seismic energy is estimated as 4×10^{18} erg as shown in Fig. 8:   The energy of explosions is about 10 times

of the deficiency of seismic energy.   This roughly holdes true in the other two cases.

As mentioned previously, the seismic activities are parallel to the deformation activities, and it may be expected that the deformations would stop whenever the earthquakes do so.   Therefore the above facts indicate that the energies of the three kinds, i.e. explosion, earthquake and deformation, have a constant amount in total which is estimated at 4.2×10^{19} erg.   Considering that the deficiency of seismic energy amounts to 4×10^{18} erg, we may say that the deficiency of deformation energy is equal to 3.8×10^{19} erg. In other words, the deformation energy may be about 10 times as large as the seismic wave energy.

During 2nd Stage, the discharge of total energy of volcanic activities was decreasing exponentially.   However, the surface eruptivity became violent for July, August and September 1978 on the contrary to the above decreasing tendency of the energy.   This is because the surface eruptivity should be governed not only by the discharge of total energy but also by the depth to the magma.

5. Prediction of the total seismic energy and the ultimate heights of the domes

The following predictions of the activities of Usu Volcano were made in June 1978 on the basis of the observational data obtained during the preceding 5 months.

Prediction of the total seismic energy which is to be released by the volcanic earthquakes

The changes in discharge rate of seismic energy during 5 months from February to June 1978 are approximated by an exponential curve $(U_2 = U_{02} e^{-\lambda_2 t})$. And by the method of least square, the coefficients are determined as follows:

$$U_2 = 2.3 \times 10^{18} \, e^{-0.0066t} \qquad \text{(erg/day)} \ . \tag{5}$$

The integrated sum of discharge rate from t=0 to t=t is expressed by

$$E = \int_0^t U_2 \, dt = \frac{E_{02}}{\lambda_2} \left(1 - e^{-\lambda_2 t}\right) \ , \tag{6}$$

and the whole seismic energy will be released at $t=\infty$ and we get

$$E_\infty = \frac{E_{02}}{\lambda_2} = 3.5 \times 10^{20}. \qquad \text{(erg)} \tag{7}$$

The energy actually released during Eruption Stage and 1st Stage is esti-
mated as 4.4×10^{20} erg. Therefore the total energy from the beginning to
the end of the present activities should amount to 7.9×10^{20} erg corresponding
to an earthquake larger than M 6.0. Already the energy of 6.7×10^{20} erg
which is 85% of the total amount, was discharged by the end of June 1978.

Prediction of the ultimate heights which are to be achieved by the new cryptodomes

During the early period of 2nd Stage, the beginning of February to
the end of June 1978, the changes are approximated by exponential curves
$(V_2 = V_{02} e^{-\lambda_2 t})$:

$$\text{Ogariyama} \quad : \quad V_2 = 37.5\, e^{-0.0079t} , \tag{8}$$

$$\text{New-mountain} : \quad V_2 = 45.6\, e^{-0.0101t} , \tag{9}$$

where the unit is cm/day.

The upheaval from $t=0$ to $t=t$ is expressed by the integrated sum of
upheaval rates:

$$\varDelta H = \int_0^t V_2\, dt = \frac{V_{02}}{\lambda_2} (1 - e^{-\lambda_2 t}) , \tag{10}$$

and the ultimate upheaval will be achieved at $t=\infty$:

$$\varDelta H = \frac{V_{02}}{\lambda_2} . \tag{11}$$

By the method of least square, we can determine V_{02} and λ_2:

$$\text{Ogariyama} \quad : \quad \varDelta H_\infty = 47.72\,\text{m} , \tag{12}$$

$$\text{New-mountain} : \quad \varDelta H_\infty = 49.14\,\text{m} . \tag{13}$$

The ultimate heights should be the sums of the initial heights H_0 and $\varDelta H_\infty$. In
Fig. 5, the initial heights of both the domes (on Feb. 8, 1978) are about 585 m
a.s.l. The ultimate heights of both the domes may be predicted as about
635 m a.s.l.

Correlation between discharge of seismic energy and uphearvals of the cryptodomes

As already shown in Fig. 7, discharge of seismic energy is proportional to
upheavals of the cryptodomes. The integrated sum of seismic energy
diacharged by volcanic earthquakes since the outbrust in August 1977 is
plotted against the heights a.s.l. of the two cryptodomes in Fig. 9 where S and P

denote the initial heights before the outburst and the ultimate amount of
energy and heights predicted from the data before July 1, 1978 respectively.
P is determined on the assumption that both the rates will decrease according
to the averaged decay coefficient of energy discharges and upheavals. The
disaccord of the decay constants λ between discharge rate of seismic energy
and upheaval rates is partly due to the differences in the accuracies of the
eatimations and partly to those in the characteristics of the phenomena.
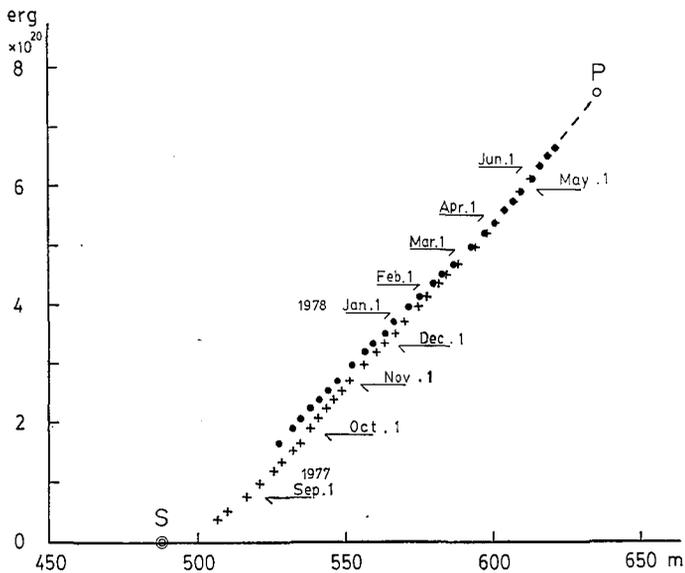

Fig. 9   Correlation between the integrated sum of seismic energy and the heights
a.s.l. of the cryptodomes.
Solid cricle: New-mountain   Cross: Ogariyama

Verification of the predictions

As a matter of fact, the predicted ultimate amount of seismic energy was
fully discharged by Apr. 7, 1979 and the predicted ultimate heights of
Ogariyama and New-mountain were achieved on Nov. 14 and on Dec. 9, 1978
respectively.   Such disaccords of the periods derive from the differences in
the decay constants of the phenomena.   The reasons for these failures are
that both the patterns of discharge of seismic energy and upheavals of the
cryptodomes have changed to keep almost constant rates after October 1978
when the explosive activities stopped.   The seismic activities and deforma-

tions have persistently continued for a year (up to October 1979) though their rates have not been large, 4.0×10^{17} erg/day and 5 cm/day in average respectively, both being about one twentieth of their highest values.   As seen in Fig. 4, during the last 6 months from April to September 1979, the pattern of earthquake occurrence has gradually changed to be more spasmodic, and the discharge rate of seismic energy has scarcely changed. Strictly speaking, the running average of the rate for 31 days has decreased only about 10% for these 6 months.

At present we may predict that the above activities would continue with almost constant rates for a while.   For the coming year, the annual discharge of seismic energy would amount to about 1.3×10^{20} erg (an earthquake M 5.5) and the annual upheavals to about 18 m.

In respect to the above persistent activities, the following episode in former days may be worthwhile to be mentioned:

In 1889 Ishikawa[5] went up to the summit of Usu Volcano accompanied by a local inhabitant who was surprised to see that a small hill had grown at the southern foot of Oo-Usu lava dome within the summit crater since he last came there 8 or 9 years ago.   The hight of the hill was not reported but this hill must be "Ogariyama" (growing mountain).   Before the 1977 eruptions, its relative hight was about 47 m and a dacite lava of 2 m×2 m area was exposed at its top.   After the outburst, the hill was cut by an east-west fault and the northern side began to upheave as shown in Figs. 2 and 5.   If we adopt the above statement, the upheaval rate of the past Ogariyama may be estimated as larger than 1.5 cm/day in average.   This rate might be possible in the past considering the results of the present observations.

6. Conclusions

Predictions of developments in the 1977~78 activities of Usu Volcano were made by means of consideration for energy discharge.   The method proved to be adequate, in this case, to predict general tendency, rise or fall, in volcanic activities though the real development in a strict sense, deviated from the predictions after several months.

Considerations for energies of volcanic activities may hold true only when the other features of the activities such as distribution of hypocenters or origin of deformations, are studied well.   Predictions with consideration for energy discharge may be useful only for activities for a certain period at particular volcano.

For the time being, we have to make efforts to find the most adequate methods to predict volcanic activities for particular period at each volcano.

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