4. *Geomagnetic Studies of Volcano Mihara. 7th Paper.* *(Possible Thermal Process Related to Changes in the Geomagnetic Field)*

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1. Introduction

Changes in the geomagnetic field accompanying eruptions of basaltic volcanoes were observed first at the time of the 1940 eruption of Volcano Miyakeshima1). Since the 1950 eruption, occurrences of the local anomalous changes of the same sort have been unquestionably verified on Volcano Mihara in Ooshima Island by various means such as dip-surveys over the island, absolute measurements of three geomagnetic components with high accuracies at 12 stations and continuous observation of changes in the geomagnetic declination at a particular station at the west coast of the island2).

Since the first discovery of the local anomalous change, the changes in the geomagnetic field associated with volcanic eruptions have been considered to be caused by thermal changes beneath the volcano though the detailed mechanism is still unknown. During the past several years, however, the writer has accumulated data from which we may infer possible thermal processes in Volcano Mihara. The purpose of this report is to attempt a quantitative estimate of the heating and cooling that account respectively for the demagnetization and magnetization within the volcano. The amount of heat thus estimated would give some clue to the study of the thermal energy of volcanic phenomena.

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1) R. TAKAHASI and K. HIRANO, *Bull. Earthq. Res. Inst.*, **19** (1941), 82, 373.
T. NAGATA, *Bull. Earthq. Res. Inst.*, **19** (1941), 335.
T. MINAKAMI. *Bull. Earthq. Res. Inst.*, **19** (1941), 356.
Y. KATO, *Proc. Imp. Acad. Japan*, (1940), 440.

2) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 161, 499.
T. RIKITAKE, I. YOKOYAMA, A. OKADA and Y. HISHIYAMA, *Bull. Earthq. Res. Inst.*, **29** (1951), 583.
I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **32** (1954), 17, 169.
I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **33** (1955), 251.

2. Geomagnetic changes in the case of the 1953–54 eruption

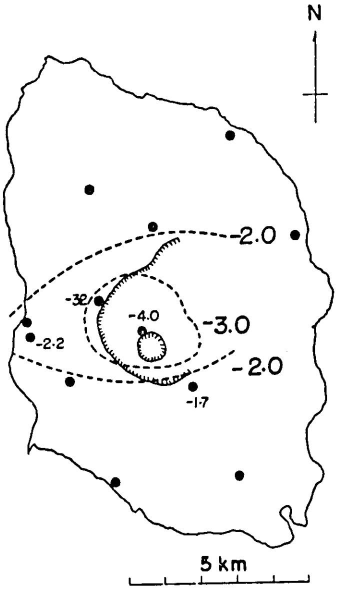

Fig. 1. Changes in geomagnetic dip accompanied by the minor eruption in Oct. 1953.

As already reported, we observed a decrease of dip-angle on Volcano Mihara during a period between August and October, 1953, while a minor eruption was reported in Oct. 1953 (see Fig. 1). The pattern of the distribution of the anomalous change is similar to that of the 1950 eruption though the amount of the decrease is much smaller on this occasion. The declination variometer that has been working at Nomashi, a station at the west coast of the island, since 1951 recorded the increase and decrease of the westerly declination as is reproduced in Fig. 2. On referring to Fig. 2, we see that the decrease of dip-angle would be maximum toward February, 1954, provided the decrease of dip-angle is assumed to be proportional to that of the declination at Nomashi. This assumption is to be proved by equations (1) and (2) in the later part of this section. Althongh no dip-survey was carried out in February, we may assume that the decrease of dip-angle at this time was approximately 9 *minutes* of arc, this figure being deduced from the fact that the change in the declination at the same time is 3 *minutes* of arc, because a decrease of dip-angle of 3 *minutes* of arc and a change of declination of 1 *minute* of arc were observed as the differences during a period between Aug. and Oct., 1953.

We are also going to assume that the 1953–54 change is caused by an apparent magnetic dipole under the volcano, such simplification having been successful since the great eruption of 1950. In order to estimate the strength of the supposed dipole, the changes in both dip-angle and declination can be utilized. As has been done in the analysis of the 1950 eruption, we presume that the direction of the dipole coincides with that of the normal geomagnetic field in this district, so that the intensity and depth of the dipole are to be determined by combining the observations of the dip-angle with those of the declination.

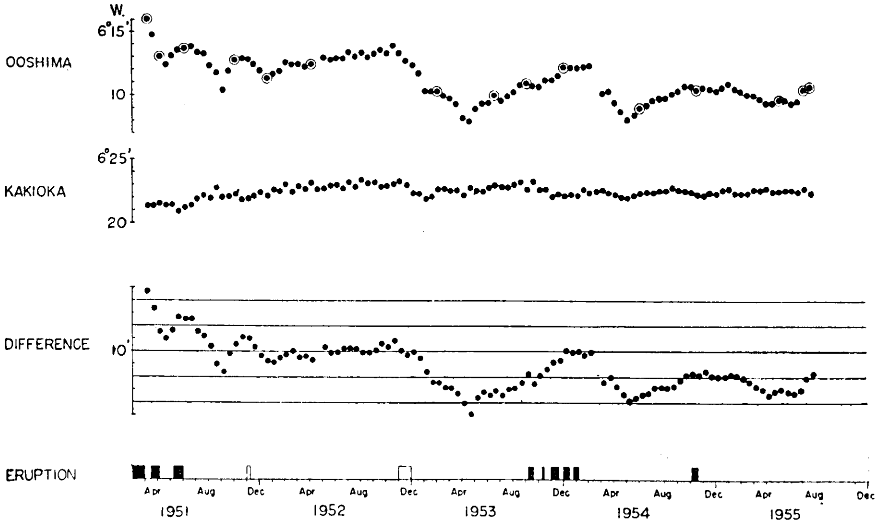

Fig. 2. The semi-monthly means of the westerly declination and activities of Volcano Mihara. Eruption is shown in an arbitrary scale.

Local deviation of the dip-angle right above the dipole satisfies the following formula

$$f(\Delta I)=\frac{\tan(I_0+\Delta I)-\tan I_0}{\tan I_0}\doteqdot\frac{\Delta Z}{Z_0}-\frac{\Delta H}{H_0} \tag{1}$$

where

$$\Delta Z=-\frac{2M}{(d+h)^3}\sin\theta$$

and

$$\Delta H=\frac{M}{(d+h)^3}\cos\theta\,.$$

M, *d* and θ denote respectively the intensity, depth below sea-level and dip of the dipole, while *h* denotes the altitude above sea-level of the observation point.

Then we obtain

$$M=\frac{\tan(I_0+\Delta I)-\tan I_0}{\tan I_0}(d+h)^3\frac{1}{2\dfrac{\sin\theta}{Z_0}-\dfrac{\cos\theta}{H_0}}\,. \tag{2}$$

Fig. 3 shows $M-d$ curves for the changes $\Delta I=3$ and 9 *minutes* of arc where it is assumed that $I_0=52°19'$, $\theta=48°$, $H_0=0.285\Gamma$, $Z_0=0.368\Gamma$ and $h=500\,m$.

Next, the westward change in declination at sea-level due west from the centre of the volcano is expressed as follows ;

$$\Delta D=\frac{\Delta Y}{H_0}=\frac{3}{H_0}\frac{wdM\sin\theta}{(\sqrt{w^2+d^2})^5} \qquad (3)$$

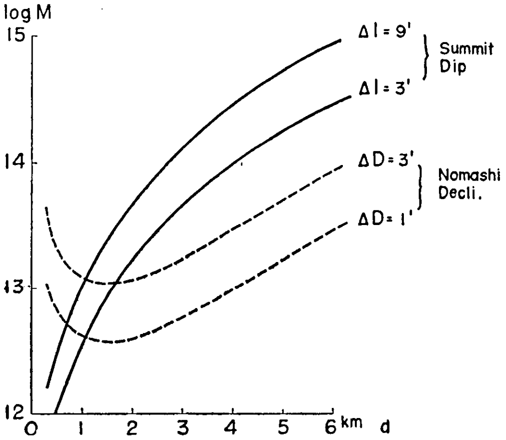

Fig. 3. Intensity M and depth d of the dipole for the changes of dip and declination.

where w is the horizontal distance between the observation point in question and the supposed dipole. Taking w as 3 *km*, $M-d$ curves for the changes $\Delta D=1$ and 3 *minutes* of arc are also shown in Fig. 3.

According to Fig. 3, the depth of the dipole in the geomagnetic field is surmised to be about 1 *km* below the sea-level, while the intensity of the dipole is estimated at 1.2×10^{13} *emu*. In other words, it is likely that this amount of magnetization of a certain region in the volcano disappeared in about 5 months after Aug., 1953. After Feb., 1954, however, almost the same amount of magnetization recovered in almost the same period in accordance with the decrease in volcanic activity.

From the equations (2) and (3), we can easily see that both ΔI and ΔD are proportional to the intensity M provided the depth of the dipole d is kept constant.

3. Thermal process responsible for the changes in the geomagnetic field in the case of the 1953–54 eruption

Changes in the geomagnetic field accompanied the eruption of Volcano Mihara since 1950 have been analysed by T. Rikitake and the present writer and are summarized as shown in Table I. The first case corresponds to the one that occurred during a period between the beginning and the most violent stage of the 1950–51 eruption, while the second is obtained during the later part of recovery stage of the first one. As was discussed in the 4th report, the time needed for the recovery of the 1950–51 eruption would be about three years. The last case is associated with a moderate eruption as stated in the last section, its development and decay having been continuously observed by the declination-variometer. In view of the well-examined geomagnetic data as well as the description of the eruption, the writer would here like to take the 1953–54 eruption as the example for constructing a model of the possible thermal processes by which the changes in the geomagnetic field are fully explained. The most important point is the possibility of heating and cooling that account for the demagnetization and magnetization of the supposed dipole as discussed in the last section. The fact that the local anomalous change occurs and decays within a few months' time should also be examined.

Table I. The hypothetical dipoles for various periods.

Period	Intensity of dipole	Depth of dipole
July 1950——Sept. 1950	$-6.3\times10^{14}\,emu$	$5.5\,km$
May 1951——Aug. 1953	$+8.6\times10^{13}\,emu$	$4.7\,km$
{ Aug. 1953——Jan. 1954	$-1.2\times10^{13}\,emu$	$1.6\,km$
{ Jan. 1954——June 1954	$+1.2\times10^{13}\,emu$	〃

According to the forgoing analyses, observed facts in the case of the 1953–54 eruption are summarized as follows ;

Changes of dipole-moment is $1.2\times10^{13}\,emu$.
Depth of the dipole is about $1.6\,km$.
Periods needed for both demagnetization and recovery are about 5 months.

The mass of lava which contributes to the change of dipole-moment ΔM is estimated from the following relation under the assumption that the lava shapes a sphere of radius r ;

$$\Delta M=\frac{4}{3}\pi r^3\Delta J(T) \tag{4}$$

where ΔJ is the change of magnetization which depends on temperature of rocks as shown in Fig. 4. As far as the basalt from Volcano Mihara is concerned, its thermal remanent magnetization is fairly large compared with its induced magnetization in the earth's magnetic field, so that the latter magnetization is utterly omitted in the following discussion. It is not necessary to consider that temperature of all part of the lava in the region considered became higher than Curie-point (about 600°C). If we assume that the temperature of the whole mass rises from 100° to 350°C, $\Delta J(T)$ becomes about 0.03 *emu/cc* as can be seen in Fig. 5, where this amount of magnetization having been obtained as the mean magnetization of several rock-samples. Therefore we get the value of r to be about 440 m from (4). The internal temperature of volcano would be higher than that calculated according to the usual law of geothermal gradient even if the volcano is not in an eruptive state, so that the initial temperature considered above may be adopted for the first approximation. The mass of the sphere is easily estimated at 9.0×10^8 *tons* when the density of the rock is taken to be 2.5 *gr/cc*. The amount of heat that is necessary for heating the whole sphere from 100° to 350°C is given as follows ;

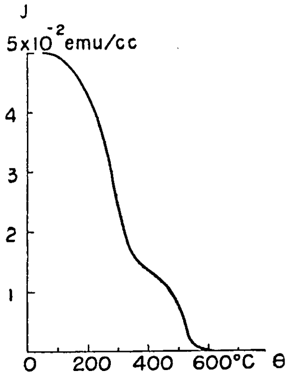

Fig. 4. Thermal remanent magnetization of the basalt from Volcano Mihara. (After T. Nagata)

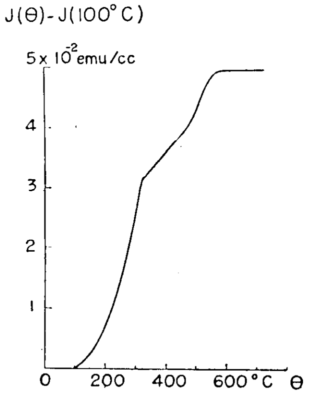

Fig. 5. Demagnetization due to the temperature rise from 100°C.

$$9.0\times10^{14}\,gr\times0.2\,cal/gr\cdot degree\times250\,degree=4.5\times10^{16}\,cal \qquad (5)$$

where the specific heat of basaltic rock is taken to be 0.2 *cal/gr·degree.*

Now we are in a position to examine whether or not such a large mass of lava which weighs 9.0×10^8 *tons* can be heated up or cooled down in a temperature range of 250°C within 5 months' time when an activity of the volcano is going up or down. If the sphere or spherical shell is a solid mass, it is almost impossible as has been suggested by Ingersoll-Zobel-Ingersoll's text[3] (concerning the cooling of a laccolith: see Fig. 6) or R. Takahasi's paper[4]. In order to avoid this difficulty, the writer presumes many cracks which divide the mass into a number of small unit-spheres. It seems natural to suppose many cracks within the volcano when we look at ejected lava from the crater-rim of the volcano. When volcanic activity is taking place, it is assumed that the surfaces of the unit-spheres are always kept at 1100°C, while it is also assumed that the surfaces are kept at 100°C when the activity is suspended. To make a rough estimation of the diameter of the unit-sphere which harmonizes with the observed facts, heat-conduction in a unit-sphere will be discussed in the following.

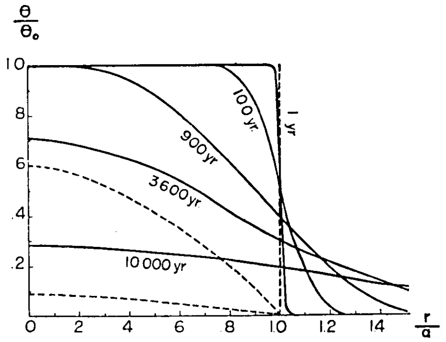

Fig. 6. Cooling-curves for a laccolith 1,000 *m* in radius for various periods of time. Broken lines show the curves for the periods of 3,600 and 10,000 *yr* when the surface is kept at 0°C.

The solution of heat-conduction in the sphere ($0 \leq r < a$) with initial zero temperature at $t=0$ is given as

$$\theta=\theta_0+\frac{2a\theta_0}{\pi r}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\frac{n\pi r}{a}e^{-\kappa n^2\pi^2 t/a^2} \qquad (6)$$

under the condition that the surface temperature is always kept at $\theta=\theta_0$. In the expression, κ, t and r are diffusivity of rock, time and distance from the centre of the sphere respectively. Hence the mean temperature of the sphere is given as

$$\theta_{\mathrm{mean}}=\theta_0-\frac{6\theta_0}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}e^{-\kappa n^2\pi^2 t/a^2} \qquad (7)$$

where κ stands for $K/C\rho$ (K: thermal conductivity, C: specific heat and ρ: density) which is estimated at about $10^{-2}\,C.G.S.$ for subterranean basalt. The changes of the mean temperature with passage of time

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[3] L. R. Ingersoll, O. J. Zobel and A. C. Ingersoll, *Heat Conduction* (1954), 141.

[4] R. Takahasi and K. Hirano, *Bull. Earthq. Res. Inst.*, **19** (1941), 379.

for several values of radius a are shown in Fig. 7. It is seen in the figure that the increase or decrease of the mean temperature of the sphere whose radius is less than 50 m exceed 250°C after $10^7 sec$ (about 4 months) provided the temperature difference between the sphere and the surrounding is assumed to be 1000°C at $t=0$.

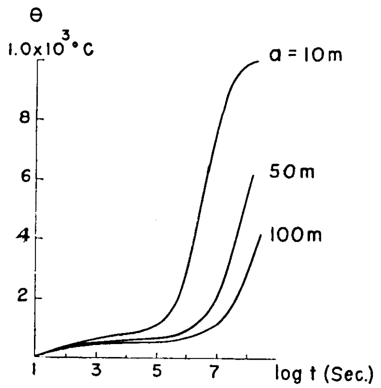

Fig. 7. Changes of the mean temperature for the various values of radius.

In the next place, the conduction in the unit-sphere of rock will be discussed in detail in relation to the demagnetization or magnetization of the whole rock-mass.

a). Demagnetization due to the rise of temperature.

With the aid of eq. (6), temperature-distributions in the spheres whose radii are 50 and 10 m at $t=10^7 sec$ are respectively obtained as shown by full lines in Figs. 8 and 9 while the surface temperature is always kept at 1100°C, κ being taken to be 10^{-2} $C.G.S.$ as before.

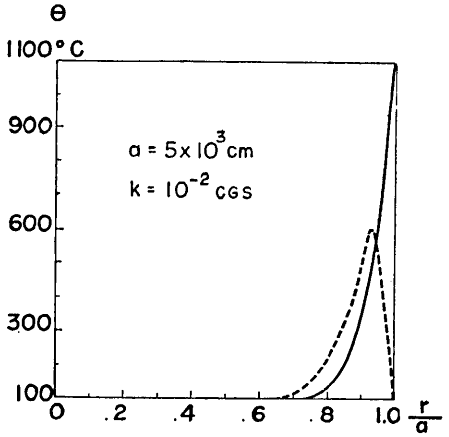

Fig. 8. Temperature-distributions in the sphere whose radius is 50 m.

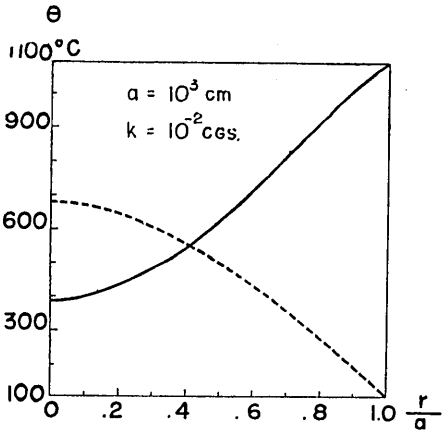

Fig. 9. Temperature-distributions in the sphere whose radius is 10 m.

The temperature distributions thus estimated specify the extent of demagnetization as can be obtained graphically from Fig. 5. Since we have got the extent of demagnetization at every part of the sphere, the whole demagnetization of the sphere can be integrated numerically by use of Figs. 8 and 9. The demagnetization of a unit-sphere thus calculated is given for the two cases of $a=50$ and $10\,m$. One example of the procedure is shown at foot-note.

$$a=50\,m\ :\ 9.0\times10^{9}\,emu\,,\qquad a=10\,m\ :\ 2.0\times10^{8}\,emu\,.$$

The whole loss of magnetization within the volcano can be easily calculated because the number of the unit-sphere included in the region, which becomes hot by the activity, is known, the effect of the mutual interaction among the unit-spheres being ignored. Then total loss of the magnetic moment of the dipole becomes as follows ;

$$a=50\,m\ :\ 3.6\times10^{14}\,emu\,,\qquad a=10\,m\ :\ 1.0\times10^{15}\,emu\,.$$

These figures surpass the amount of the dipole-moment which is responsible for the anomalous change in the geomagnetic field.

b). *Magnetization due to cooling.*

The temperature-distribution in the sphere, of which the initial temperature is given as $f(r)$, is given by

$$\theta=\frac{2}{ar}\sum_{n=1}^{\infty}e^{-\kappa n^2\pi^2 t/a^2}\sin\frac{n\pi r}{a}$$
$$\times\left\{\int_0^a r'f(r')\sin\frac{n\pi r'}{a}dr'-n\pi\kappa(-1)^n\theta_0\int_0^t e^{\kappa n^2\pi^2\lambda/a^2}d\lambda\right\}\,. \qquad (8)$$

The surface temperature is always kept at $\theta=\theta_0$ as before. Here taking the full-line curves in Figs. 8 and 9 as $f(r)$, the distributions at $t=10^7$

Radius r	Temp. θ	$J(\theta)-J(100°\mathrm{C})$	Volume	Demagne. ΔM
$\times a(50m)$	°c	$\times10^{-2}\,emu/cc$	$\times10^{10}cc$	$\times10^{8}emu$
0.70～0.75	100	0.0	4.1	0.0
0.75～0.80	120	0.1	4.7	0.5
0.80～0.85	170	0.4	5.4	2.2
0.85～0.90	260	3.3	6.0	19.8
0.90～0.95	500	4.3	6.7	28.8
0.95～1.00	900	5.0	7.5	37.5
				$88.8\times10^{8}\,emu$

Total demagnetization:

$$8.9\times10^{9}\,emu\times\frac{2.1\times10^{16}\,cc}{5.2\times10^{11}\,cc}\ \text{(number of the unit-sphere)}=3.6\times10^{14}\,emu$$

sec are given by dotted curves in those figures where the surface temperature is assumed to be 100°C. The assumption of the surface temperature will be possible if we take into account the effect of the contact of the sphere with subterranean water after the incandescent molten lava withdrew downward.

By means of procedures similar to the former case, totals of recovered moment of the dipole are estimated as follows;

$$a=50\,m\ :\ 4.8\times10^{13}\,emu\,,\qquad a=10\,m\ :\ 4.5\times10^{14}\,emu\,.$$

We see that the magnetic moment lost in active stage can not be wholly restored within the period, the residues amounting to 87 and 55% respectively. Although it seems difficult to explain the whole recovery which is shown in Fig. 2 by the process discussed here, the fact that the process can account for half of the recovery should be noted. When we take into consideration the fact that the cooling would occur from the top of the hot region, the effect of the colling on the geomagnetic field on the surface of the volcano would be much larger than that of the heating which will take place from the bottom because the distance between the surface and the top will be less than one half of that between the surface and the bottom. Thus there might be a possibility of explaining the rather quick recovery though nothing accurate can be said at the present stage of investigation.

4. Cooling by expansion of water-vapour

As is discussed in the last section, heat-supply from the deep to magma-reservoir may be considered to be sufficient for the supposed thermal process in the demagnetization stage. However, the cooling process would only be possible by thermal conduction into the surrounding medium together with expansion of water-vapour from a depth of about 2 *km* to the earth's surface. Here, we are only going to discuss the expansion of water-vapour. The amount of heat to be dissipated in the cooling period should be approximately equal to that obtained at the active stage, namely $4.5\times10^{16}\,cal$ as given by (5), so that it is necessary to take out this order of heat from the reservoir in order to explain the geomagnetic change during the cooling period.

Adiabatic expansion has essentially no effect upon the cooling of the lava-mass, but it contributes to the efficiency of the vertical conduction of heat through the crater-vent. The theoretical limit of the cooling effect by adiabatic processes is given by considering the expansion to infinity. Taking into account the dependency on temperature, the limit is given as

$$W_\infty = C_v T . \tag{7}$$

Introducing $C_v=0.33$ and $T=273+1100$, we obtain

$$W_\infty = 4.5 \times 10^2\,cal/gr .$$

In the case of isothermal expansion, the work done by water-vapour is given by

$$W = RT_0 \int_{v_0}^{v} \frac{dv}{v} , \tag{8}$$

where we assume that water-vapour can be treated as ideal gas. Considering that hydrostatic pressure is about 400 *atm* at the depth of 2*k*m, we get

$$W = 9.0 \times 10^2\,cal/gr .$$

It seems likely that the actual expansion will give a value between the two extreme cases stated above. Thus, the heat-loss by expansion of water-vapour is deemed at $7 \times 10^2\,cal/gr$ in our order-estimation.

As for sources of water-vapour, the juveniles from the hydrous magma which swelled up from the deep as well as subterranean rain-water are thought of. Here, we will consider the total mass of water contained in the magma reservoir which shapes aspherical shell beneath the volcano. The internal volume of the spherical shell, whose radius is say 300 *m*, is $1.1 \times 10^{14}\,cc$, its mass being $2.8 \times 10^8\,tons$. According to R. W. Goranson[5], the water-content in basaltic rocks amounts to about 5%. Therefore, the mass of ejected water-vapour from the foresaid lava is to reach the total of $1.4 \times 10^7\,tons$. If this amount of water is to be ejected during a period of $10^7\,sec$, the mean mass of water-vapour that is ejected per unit time is about 1 *ton/sec*. The latter figure is probable, if we refer to S. Murauchi's observations[6] in the case of the 1950–51 eruption. After all, the amount of heat to be dissipated by thermal expansion of water-vapour is estimated at $1.0 \times 10^{16}\,cal$ which is not far from the expected figures.

If we take into account other factors, for example, heat-conduction into the surrounding region which is fully discussed in the last section, the explanation of the recovery phase of the local anomalous change by

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[5] R. W. GORANSON, *Amer. Jour. Sci.*, **21** (1931), 481.

[6] S. MURAUCHI, *Bull. Natur. Sci. Mus.*, **20** (1953), 70.

cooling of the lava-mass seems to be not impossible. It is also likely that the subterranean water will play an important role in the cooling though a quantitative estimate of its effect would be quite difficult.

5. Summary and conclusion

Summarizing the results obtained by the geomagnetic observations on the occasion of the 1953–54 eruption, the writer tried to explain the anomalous changes in the geomagnetic field accompanied the eruption by considering possible thermal processes beneath the volcano. Generally speaking, violent heat-supply from the depth is probably conceivable while cooling-factors are restricted by the external conditions. If we suppose many cracks which divide the subterranean mass of lava into numerous small unit-spheres, it is possible to explain the heating process quantitatively. On the other hand, only half of the recovery is accountable by the cooling process under this assumption. However, the other half seems capable of interpretation by the supplementary consideration concerning the cooling by expansion of water-vapour from the depth to the earth's surface.

In short, it seems possible to construct a model of the thermal processes which are responsible for the changes in the geomagnetic field though some reasonable assumptions are necessary.

In concluding, the writer wishes to express his hearty thanks to Dr. T. Rikitake for his helpful advice.

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4. 三原山の地球磁気学的研究　第 7 報
(地球磁場の変化を説明する熱過程)

地震研究所　**横　山　　泉**

1950 年の噴火以来，大島三原山において，種々の方法によつて地球磁場の変化が観測されてきたことは既報の通りである．この種の火山活動に伴う地球磁場の変化を完全に説明することは，勿論時期尚早ではあるが，如何なる仮定の下に如何なる熱過程が考えられるかを変化の推移が割合よくわかつている 1953–54 年の異常変化を例として考えた．今迄考えられたような充実球の熱伝導では勿論説明不可能である．そこで，この熔岩に亀裂を考え，小さな単位球の集合とみなして，それらの熱伝導を調べると，この単位球の半径を数 10m とすれば観測結果を説明し得る．

冷却過程における放熱が如何にして行われるかが問題である．玄武岩塊から外への熱伝導も勿論考えられるが，地下の水蒸気が地表へ噴出膨脹する際に奪う熱量だけを調べてみても，大体帯磁に必要な放熱を説明出来るようである．水蒸気の源としては熔岩そのもの及び降雨の浸透等が考えられる．

要するに 1950 年以来，三原山噴火に際して観測された地球磁場の異常変化は，ある程度許容される仮定の下では，全然説明不可能な現象ではない．
