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21. *An Interpretation of the Transient Geomagnetic Variations Accompanying the Volcanic Activities at Volcano Mihara, Oshima Island, Japan.*

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Summary

The reversible change in the geomagnetic declination accompanying the major activities of Volcano Mihara, Oshima Island, has been interpreted as being due to heating and cooling, or demagnetization and remagnetization of a subterranean mass at a depth of a few km. In the present paper, an alternative way of interpreting the observation is proposed. In the new model, the heated region is assumed to be a cylinder ($r \cong 430\,m$) extending from the depths to the surface crater. It is shown that the gradual heating of the cylinder from beneath would produce the apparently reversible change in the declination, without requiring any rapid cooling which has been the difficulty in the classical model. Even in the new model, the transfer of heat both in the heating and cooling of the cylinder would need some process such as convective transfer, which is much more effective than the ordinary conductive one.

1. Introduction

A number of investigations have been carried out on the geomagnetic anomaly associated with volcanoes and its variations accompanying the eruptive activity.[1)~11)] In particular, T. Rikitake and I. Yokoyama, with

1) T. NAGATA, *Bull. Earthq. Res. Inst.*, **16** (1938), 288.
2) T. NAGATA, *Bull. Earthq. Res. Inst.*, **19** (1941), 402.
3) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 161.
4) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 499.
5) T. RIKITAKE, I. YOKOYAMA, A. OKADA and Y. HISHIYAMA, *Bull. Earthq. Res. Inst.*, **29** (1951), 583.
6) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **32** (1954), 17, 169.
7) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **33** (1955), 251.
8) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **34** (1956), 21.
9) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **35** (1957), 327, 567.
10) T. NAGATA and S. SAKUMA, *Handbuch der Physik*, XLVIII, (1957), Springer.
11) T. RIKITAKE and I. YOKOYAMA, *J. Geophys. Res.*, **60** (1955), 165.

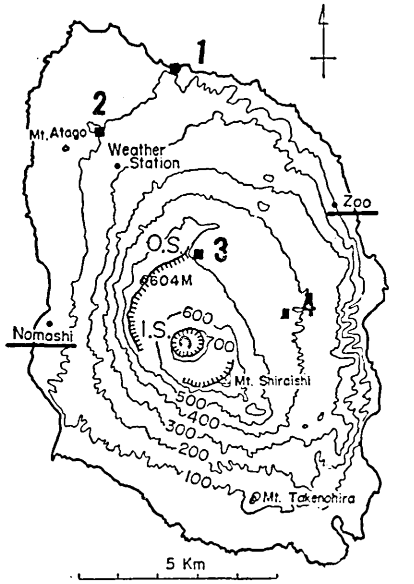

Fig. 1. Topographical map of Oshima Island. Underlined are the locations of magnetic observatories. Square dots 1, 2, 3 and 4 are the bore-holes. The temperature distributions in the holes are shown in Figs. 8, 9, 10 and 11 respectively.

others, showed by serial observation for more than ten years that the geomagnetic declination around Volcano Mihara, Oshima Island, Japan, changes on occasions of major activity. Continuous measurement of the declination has been conducted at two stations in Oshima Island as indicated in Fig. 1: at Nomashi since 1951 and at the Oshima Zoo since 1956. The results obtained at Nomashi Observatory are reproduced in Fig. 2. In Fig. 2, the difference curve is the difference in the semi-monthly mean values of the declination at Nomashi Observatory and at the Kakioka Geomagnetic Observatory on the Main Island of Japan. The difference has been taken in order to eliminate the effect of the non-local temporary variations such

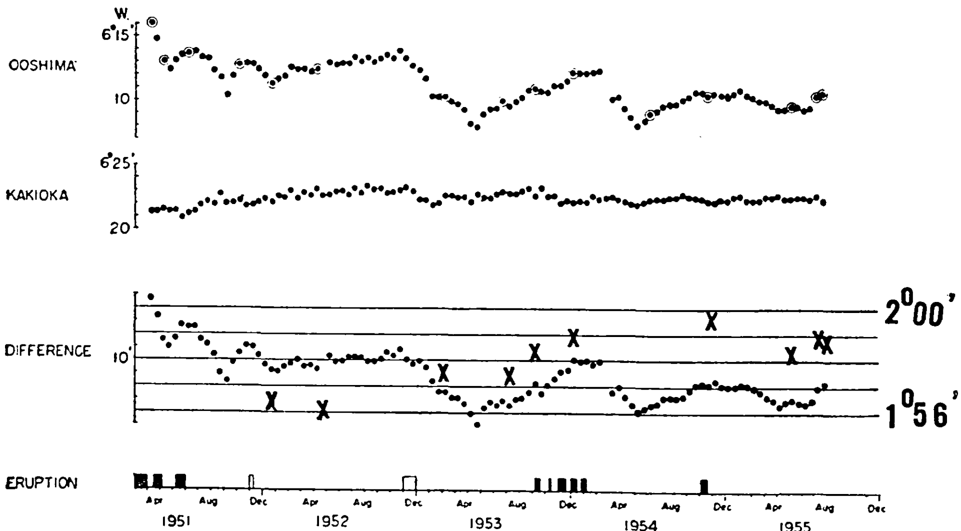

Fig. 2. The semi-monthly means of the westerly declination at Nomashi, Oshima. Eruption of Volcano Mihara is shown in an arbitrary scale. Crosses represent the dip difference between Oshima and Kakioka, referring to the scale on the right hand side. (after Yokoyama and Rikitake)

as magnetic storms. It may be closely observed in this figure that on the occasion of the 1953–1954 activity (the total amount of lava erupted in this period is estimated as 1.9×10^6 *tons*), the geomagnetic declination at Nomashi Observatory experienced an almost reversible change of some 3~4 minutes of arc: the increase in the westerly declination started a few months prior to the surface activity and apparently disappeared within a few months after the ceasing of the eruptions. Yokoyama[12),13)] suggested that this anomalous variation may be interpreted as being caused by the thermal demagnetization and re-magnetization of a subterranean basaltic mass during the above specified period of time: more precisely, the observed change may be accounted for by the disappearance and re-appearance of a magnetic dipole situated at a depth of 1.6 *km* below sea level right below the volcano. The dipole has a magnetic moment ($|M| \cong 1.2 \times 10^{13}$ *emu*) oriented parallel to the local geomagnetic force. Supposing the temperature change to be from 100°*C* to 350°*C*, and the accompanying variation of the magnetic moment $J=0.03$ *emu/cc*[14)]*, the radius r of the equivalent sphere centred at $d=1.6$ *km* was obtained as $r=440$ *m* as shown in Fig. 3. This view, as it bears a close relevance

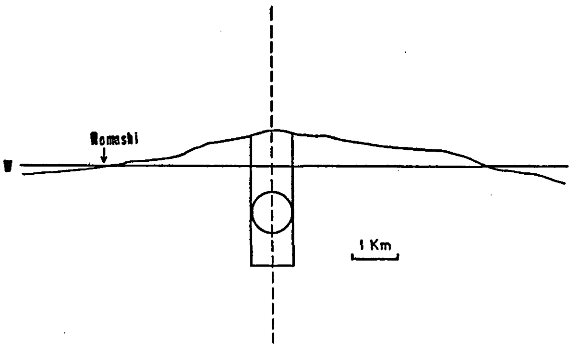

Fig. 3. East-west section of Oshima Island.

to the detail of the processes beneath the volcanoes in action, is of great importance in volcanic studies. The cause of the demagnetization, *i. e.* the heating of the mass may be taken as being the intrusion of hot magma from the depths. It seems, however, as was shown by Yokoyama[15)] that the alleged re-magnetization, *i. e.* the cooling of the above

12) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **34** (1956), 185.
13) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **35** (1957), 75, 99.
14) T. NAGATA, *Rock-magnetism*, (1953), Maruzen, Tokyo.
* Figures quoted here are the measured values for actual Oshima basalts.
15) *loc. cit.*, 12), 13).

specified spherical mass in such a short period as a few months must be achieved with difficulty unless some very effective cooling process is assumed. The model outlined above will be referred to as the classical model in the present paper.

It is intended in this paper to suggest that there may be an alternative way of interpreting the observed mode of change in the geomagnetic declination without requiring such a rapid cooling of the subterranean mass.

2. A Cylindrical Model

The geomagnetic anomaly at a point P caused by a magnetic dipole of the moment $\mathbf{M}(M_x, M_y, M_z)$ oriented parallel to the geomagnetic force $\mathbf{H}(H_0, 0, Z_0)$ can be expressed by,

$$\Delta H = M_z\left[\frac{-1}{r^3} + \frac{3x}{r^5}\left(x - d\frac{Z_0}{H_0}\right)\right\} \tag{1}$$

$$\Delta Z = 3M_z\left[\frac{-d}{r^5}\left(x - d\frac{Z_0}{H_0}\right)\frac{H_0}{Z_0} - \frac{1}{3r^3}\right] \tag{2}$$

$$\tan \Delta\delta = 3M_z\frac{y}{r^5}\left(\frac{x}{Z_0} - \frac{d}{H_0}\right) \tag{3}$$

$$\tan \Delta I = M_z\frac{\Delta Z - \frac{Z_0}{H_0}\Delta H}{H_0 + \Delta H} \tag{4}$$

where the notations are,

ΔH: anomaly in the horizontal component,
ΔZ: anomaly in the vertical component,
$\Delta\delta$: anomaly in the declination,
ΔI: anomaly in the inclination,

and r, x, and d are taken as shown in Fig. 4.

Now, let us suppose that in the period preceding the outbreak of the surface activity, the rising magma heats up a cylindrical part of the mountain during its way up and thermally demagnetizes it. In such a case, the state of affairs may be represented magnetically by the intrusion of a cylinder magnetized in the opposite direction to the geomagnetic force. In evaluating the change, in such a case, of the magnetic field at a place fairly apart from the cylinder, it may be allowable to approximate the gradual intrusion of the cylinder by a piling up of the magnetic dipoles with negative polarity. This is equivalent to approximating the magnetic field around a magnetic disc by means of a magnetic sphere.

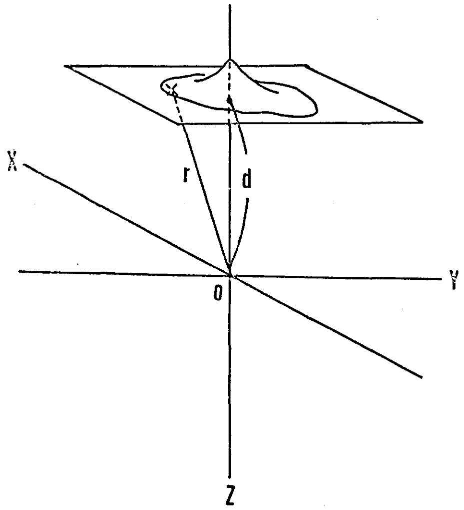

Fig. 4. The co-ordinate system.

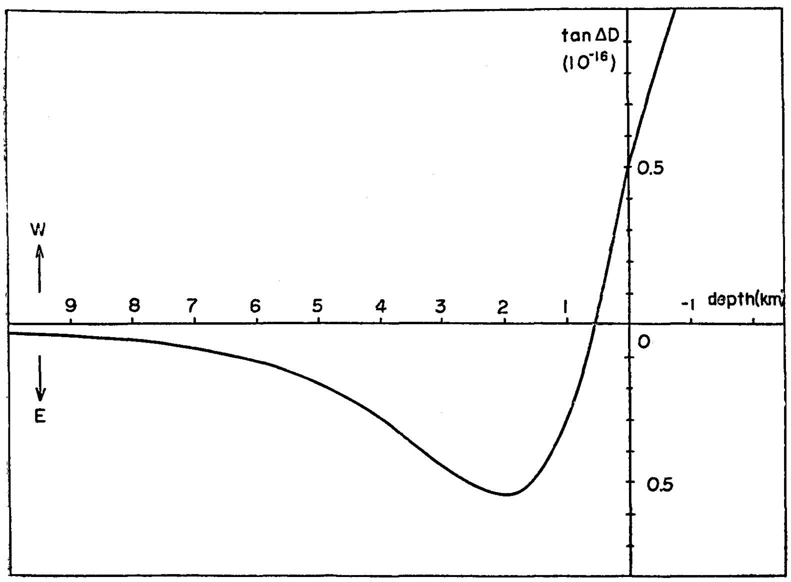

Fig. 5. The anomalous values of declination at Nomashi caused by a unit magnetic dipole with positive polarity at various depths right below the crater.

In the first place, we examine, by the formula (3), the expected anomalous values of the declination at Nomashi Observatory, caused by a unit magnetic dipole with positive polarity, placed at various depths right below the crater. We put,

$$\left.\begin{aligned} H_0&=0.295\ oe\ , \\ Z_0&=0.330\ oe\ , \\ x&=650\ m\ , \\ y&=-3250\ m\ . \end{aligned}\right\} \quad (5)$$

The results are shown in Fig. 5. To be noted in this figure is the fact that the effect on the geomagnetic declination at Nomashi Observatory is contrary, depending on whether the dipole is situated deeper than say 580 m or shallower, *i. e.*, a dipole with positive (negative) polarity at $d>580\ m$ would swing the direction of the local magnetic meridian eastward (westward) whereas a dipole at $d<580\ m$ would have the contrary effect. This fact, easily seen from the form of formula (3), suggests that it may be possible that the anomalous change in the geomagnetic declination before and after the surface eruptive activity (Fig. 2) is explained by the gradual upward growth of a pile of dipoles with negative polarity. In this model, the recovery of the declination, after activity, would not require any such rapid cooling of the deep buried temporarily demagnetized mass as in the classical model. On the contrary, it would require some demagnetization, *i. e.* the heating of the shallower part of the mountain mass to be still going on during and after the final stage of the surface activity.

In order to estimate roughly the effect of the above mentioned heating of the cylindrical part of the mountain on the declination, the following measures may be taken. Let us divide the cylindrical column to be heated (see Fig. 3) into discs, say 100 m thick, each of which may be regarded as a magnetic dipole with the identical magnetic moment **M**. **M** is antiparallel to the geomagnetic force, since it is to represent the demagnetization. We, then, sum up the anomalous declination angles due to those dipoles which are above a $-550\ m$ level following formula (3). This gives, for small $\varDelta\delta$,

$$\tan \varDelta\delta \doteqdot \varDelta\delta = 66\times10^{-19}\cdot M_z \qquad (M_z \text{ per } 100\ m \text{ thickness}) \qquad (6)$$

Taking the observed amount of the recovery in the declination (Fig. 2) as 3′ of arc, M_z per 100 m thick disc turns out to be $1.3\times10^{12}\ emu$.

giving $|\mathbf{M}|=1.8\times10^{12}$ *emu*. Since the intensity of the natural magnetization of the basaltic rocks forming the volcano is about 3×10^{-2} *emu/cc*[15], the above value of $|\mathbf{M}|$ would lead to the radius of the demagnetized column being about 430 *m*.

Thus defining the radius of the heated column, we next examine the effect of heating below the $-550\,m$ level at the stage preceding the surface activity. The observed westerly change in the declination preceding the activity is about 3′ of arc. Using formula (3) again, the effective depth of the demagnetized column to produce a 3′ anomaly in declination will be estimated numerically by,

$$\tan \Delta\delta \doteqdot M_z \sum_{d=550\mathrm{m}}^{d=D} \tan \Delta\delta \ , \qquad (7)$$

where M_z is taken as 1.3×10^{12} *emu* per 100 *m* as obtained above. Solving (7) numerically for D, we find that the demagnetization of the column between the $-550\,m$ level and some $-2{,}200\,m$ $(-D)$ would be sufficient to produce the observed change in the declination. The mode of change in the declination in the present case as a function of the depth of the top of the heated region will be as shown in Fig. 6. This mode roughly resembles the observed one shown in Fig. 2, if a constant speed for the upward movement of the lava is assumed.

In the above estimation, the value of M_z is taken to be constant from the surface to the $-2{,}200\,m$ depth, and zero below that depth. This should be far from the reality, because it is expected that the

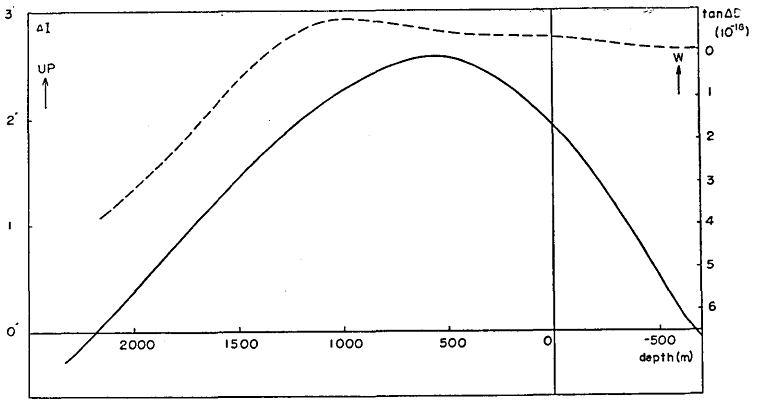

Fig. 6. Expected mode of change in the declination (solid line) and inclination (broken line) at Nomashi.

15) *loc. cit.*, 14).

general temperature beneath the active volcano increases with the depth and consequently the intensity of the natural magnetization would diminish continuously with the increase in depth. Without any definite information as to the actual temperature distribution, the argument here should be taken only to point out that the westward change in declination may be explained by the heating of the columner part deeper than say the $-550\,m$ level. In principle, the lower limit of the effective column should be the depth at which the general temperature reaches the Curie point of the ferromagnetic ingredients of the rocks.

Based on the consideration outlined above, the model to be presented here may be stated as follows. Preceding the period of major activity, the magma gradually rises from beneath, finding its way up through filling existing fissures and creating new ones. This process will heat up the columner part surrounding its major path and demagnetize it. As long as the demagnetized region is below some critical depth ($-550\,m$), the anomalous change in the geomagnetic declination at Nomashi Observatory is westward. But, after it passes this depth, the anomalous change tends eastward. When the heating near the surface of the summit is completed (this is assumed to be a few months later than the time when the lava reaches the surface, owing to slowness in the transfer of heat), the anomalous change in the declination is apparently cancelled out giving an appearance of recovery. Cooling after the end of activity would proceed more slowly, and the change in the declination accompanying this slow process would be much less pronounced than in the heating process. If, for instance, the cooling of both the upper and lower parts of the column should proceed more or less simultaneously, there would apparently be no change in the declination.

3. A Possible Check of the Model by Variations in the Geomagnetic Inclination

In the classical theory, the change in the geomagnetic declination and its recovery, accompanying volcanic activity, has been assumed to be caused by the heating and cooling of a subterranean mass. In that model, the thermal state under the volcano, a few months after the peak of the activity, is assumed to be the same as that long before the activity. It is, therefore, necessary that all of other elements of the geomagnetic field should also resume their original values. On the other hand, in the model presented in this paper, the thermal state a few months after the peak activity is quite different from the original: the former state is throught to be the most heated state and the recovery in the declination is only apparent.

Let us take the magnetic inclination or the dip angle as the example of other geomagnetic elements. As stated above, the change expected from the classical theory should be reversible with time, just as in the case of the declination. In order to estimate the possible change in the dip angle anticipated from the new model, a measure similar to that taken in estimating the declination change has been taken: *i. e.*, first calculate the anomalies in the H and Z components (ΔH and ΔZ) due to a dipole with a positive unit magnetic moment at various depths from the formulas (1) and (2) as illustrated in Fig. 7. From these results, the expected change in the dip angle accompanying the change in the declination specified in Fig. 6 can be obtained as the dotted curve in Fig. 6 shows. It may be clearly observed in the figure that the dip angle does not recover in the present model.

In Oshima Island, continuous measurement was carried out only for the declination during the active periods concerned. Data on the dip angle at Nomashi are available only for the times when occasional absolute

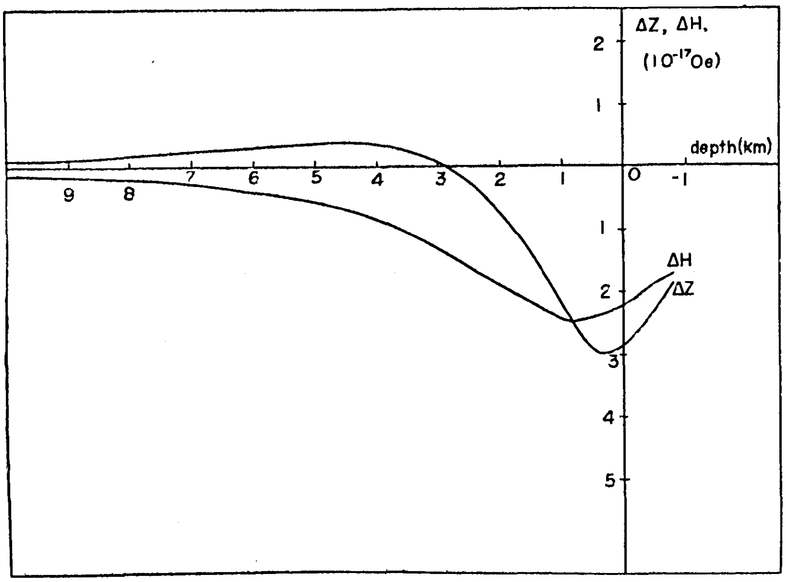

Fig. 7. The anomalous values of horizontal and vertical components at Nomashi caused by a unit magnetic dipole with positive polarity at various depths right below the crater.

measurements were conducted.* These data, though scanty, are plotted in Fig. 2 by crosses. Unfortunately the data are missing for the most critical period, *i. e.* for the middle part of 1954, so that it is not possible to say definitely if the recovery in the dip angle did or did not take place. It seems, however, that the general trend seems to fit the "non-recovery" hypothesis better, giving support to the new model. The continuous recording of the three geomagnetic components, which is now carried on at Nomashi Observatory, will provide a more definite check concerning this point in the future active periods of the volcano.

4. Discussion

The model described in the preceding sections has been devised in order to avoid the rapid cooling of the subterranean mass that was

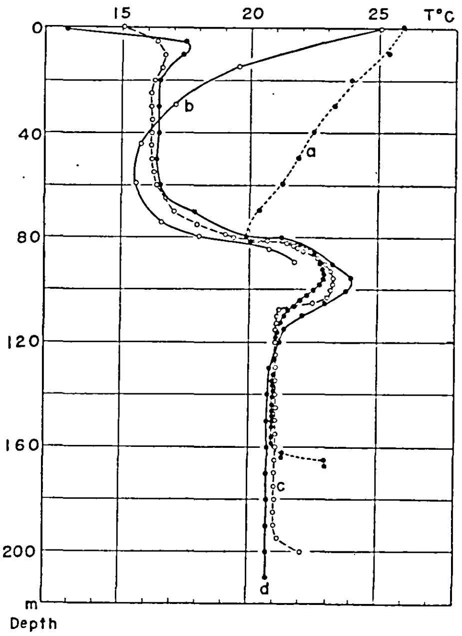

Fig. 8. Temperature distributions in the bore-hole at Okada (locality No. 1 in Fig. 1.).
a....measured on July 13, 1958.
b....measured on August 10, 1958.
c....measured on October 24, 1958.
d....measured on December 5, 1959.
(after Hôrai and Uyeda)

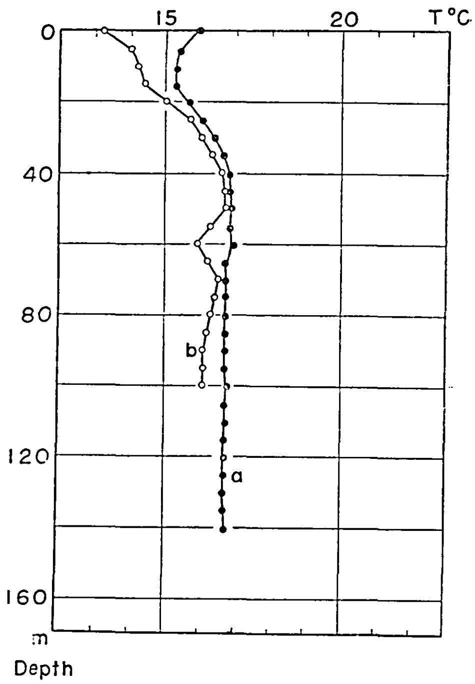

Fig. 9. Temperature distributions in the bore-hole at Jino-oka (locality No. 2 in Fig.1.).
a....measured on October 25, 1958.
b....measured on December 10, 1958.
(after Hôrai).

* By the courtesy of Dr. I. Yokoyama.

required in the classical model. In the new model no such cooling is necessary to explain the observed mode of the change in the geomagnetic field accompanying a *single* period of activity. It was reported, however, that the changes were detected for the two active periods which were in 1950–1951 and in 1953–1954 (see Fig. 2). This fact may indicate that the thermal state, disturbed in the 1950–1951 activity had substantially recovered before the 1953–1954 activity started.

The volume of the cylindrical column (430 m in radius and 3 km in height) to be heated in the present model is about 1.74×10^{15} cc and its mass would be about 4.35×10^{15} gr. The heating necessary to cause sufficient change in the declination is taken to be from 100°C to 350°C throughout the cylinder, for the sake of simplicity. Taking the specific heat of the rock 0.2 cal/gr °C, the total heat required would be some 2×10^{17} *calories*. This value is about five times as large as that in the classical model. The removing of this amount of thermal energy out of the volcano in three years seems to be a rather unusual matter. If this energy is assumed to emanate uniformly from the whole area of the Island ($\sim10^{12}$ cm^2) in three years, the rate of the heat flow would be about $2\times10^{-3}cal/cm^2$ sec, which is almost 10^3 times as large as the ordinary terrestrial heat flow. It is evident that the ordinary thermal conduction process cannot

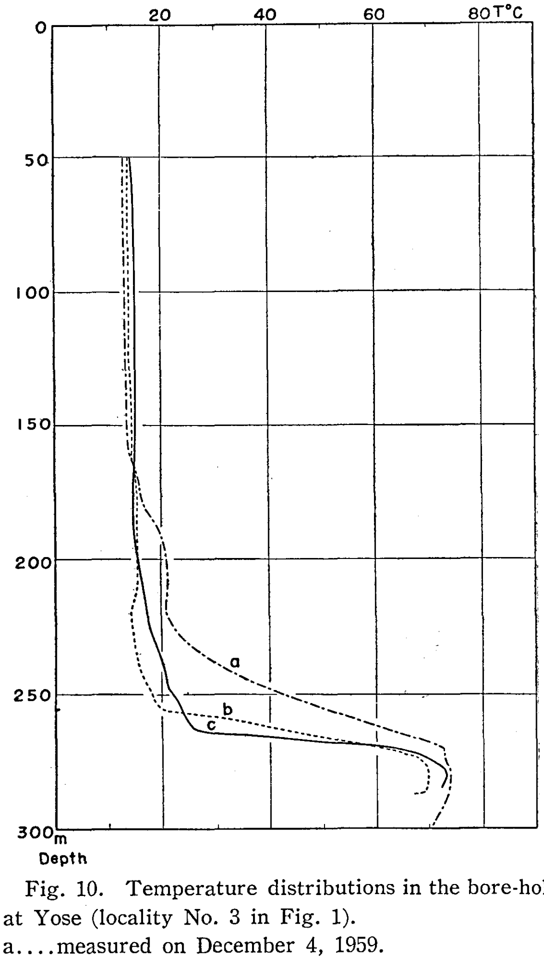

Fig. 10. Temperature distributions in the bore-hole at Yose (locality No. 3 in Fig. 1).
a....measured on December 4, 1959.
b....measured on July 27, 1960.
c....measured on December 3, 1960.
(after the Dowa Mining Company, Hôrai and Uyeda)

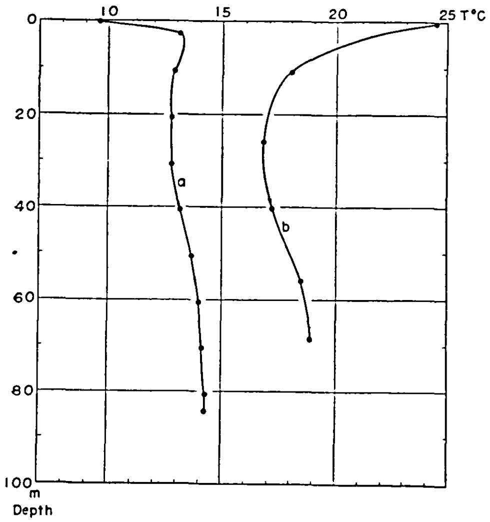

Fig. 11. Temperature distributions in the bore-holes at Sabaku (locality No. 4 in Fig. 1).
a....measured on January 22, 1960, hole No. 1.
b....measured on May 22, 1960, hole No. 2.
(after Uyeda)

bring out such an amount of heat. In fact, the near-surface geothermal gradients at several localities in the Island are known to be even less than the normal value as shown in Figs. 8, 9, 10 and 11. Such lack in the geothermal gradient indicates that the heat output through conduction may be even smaller than in ordinary non-volcanic areas. It may be considered that the heat is transferred, in such a volcanic island, by some sort of convection process and the area of upwelling of the convecting material, probably water and vapour, is concentrated more or less in the vicinity of the crater, the surrounding area being the region of sinking as J. Elder[16] points out.

The origin of the convective water may be partly jevenile and partly meteoritic. We now consider only the meteoritic water ($\sim$300 $cc/yr\ cm^2$) and assume that about one third of the total rain fall participates, through being heated to say $70°C$ and evaporating, in the above convection process. Then, it turns out that the $2\times10^{17}\,cal.$ may be carried away in three years. This estimation is extremely crude and merely an arithmetic deduction. Physical investigation of the thermal process going on inside the volcano should undoubtedly be very important.

Another point to be mentioned would be as follows. In the classical model, the heating was supposed to be concentrated in a spherical region a few kilometres deep. It was implied there that magma stays at this region for a considerable length of time and rises from there to the surface quickly. Clearly the heated region is related to the "magma reservoir". In the present model, on the contrary, no such particular place is assumed at such depth and the magma is assumed

16) J. ELDER, private communication.

to rise more or less with a constant speed all the way through. Filling all the existing cracks and fissures and creating some new ones in all directions, the magma will heat up the cylindrical volume up to the surface. In this respect, the present model does not seem to support the concept of the magma reservoir. If such a reservoir should exist at all it may be at some greater depth.

5. Acknowledgement

The author wishes to thank Drs. T. Rikitake, I. Yokoyama and John Elder, and Mr. T. Yukutake for their interest and criticism. He also acknowledges the courtesy of Mr. K. Hôrai and the Dowa Mining Company who allowed him to refer to their unpublished data on the temperature in bore holes in Oshima Island. Miss E. Nakagawa and Mr. I. Tanaoka assisted the author in drawing the diagrams.

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21. 伊豆大島における火山活動と地磁気変化についての一解釈

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伊豆大島三原山の火山活動に伴なつて，同島野増地磁気観測所では偏角に可逆的変化があることは，力武，横山らによつて確かめられている．この現象は地下数粁の深さに仮定された球状部分が，火山活動の消長に伴なつて加熱，冷却され，その磁性を失なつたり，再獲得したりするとして解釈されている．本論文では多少異なつた解釈法が提出される．新らしいモデルでは加熱される部分は半径約 430m の円筒状の部分であつて，地下深所より火口に達するとされる．このような円筒が下部から徐々に加熱されるとすると，野増観測所における偏角は見掛け上，可逆的な変化を起すことが示される．この場合には，従来のモデルで必要とされたような急速な地下球体の冷却は要求されない．ただし，新らしいモデルにおいても，数年おきに火山活動が起り，これに伴って磁場変動もあるという観測事実を説明するためには，対流現象のような効果的な熱伝達機構を山体内に仮定する必要がある．