12. *Geomagnetic Studies of Volcano Mihara. The 5th Paper.*

(Changes in Three Geomagnetic Components during the Period from May 1951 to August 1953.)

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1. Introduction.

In relation to the eruptions of Volcano Mihara in Ooshima Island, various studies were projected from the view-point of geomagnetism since 1950. It is of great importance and interest to accumulate data of changes in geomagnetic field related to volcanic activities as accurately as possible because very few studies of this sort have hitherto been made elsewhere. Generally speaking, observations with high accuracy are quite difficult to be conducted on volcanoes which are, as a rule, in places far from civilized area. However, Volcano Mihara is situated fairly near Tokyo and rather easily accessible. So that, it is desirable to get data as many as we can on this volcano before we start elaborate works on other volcanoes. The results got here would be helpful for general studies of this kind which should be carried out on any other volcanoes.

Some results obtained by a series of geomagnetic dip-surveys and continuous observation of changes in geomagnetic declination from July 1950 to Oct. 1953 have been reported in the previous papers.[1][2][3][4] Although we have reported some evidences of geomagnetic changes that are related to volcanic activities, the local anomalous changes in three geomagnetic elements during the period from May 1951 to Aug. 1953 are abstracted in this paper on the basis of the data obtained by the most accurate observations. The changes are also analyzed in order to surmise their sources.

1) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 161.
2) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 499.
3) T. RIKITAKE, I. YOKOYAMA, A. OKADA and Y. HISHIYAMA, *Bull. Earthq. Res. Inst.*, **29** (1951), 583.
4) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **32** (1954), 17.

2. The magnetic survey repeated in Aug. 1953.

As already reported in the 3rd paper, the magnetic survey with a first-order G.S.I. type magnetometer was carried out at ten stations suitably distributed in Ooshima Island in May 1951 when Volcano Mihara was still very active. In Aug. 1953 the volcano seemed to be rather quiescent in appearance and the survey was repeated with a newly constructed second-order G.S.I. type magnetometer,[5] the accuracies of which being 0.1 *minute* of arc in declination and inclination and 1γ in intensities as well as the first-order one. Station No. 42, southern foot of Shiraishiyama, was added newly in this survey for future study. The results of the observations are given in Tables I～XI. At station No. 24, Oomiya park, Nomashi Village, the azimuth failed to be determined owing to the growth of pine-trees. And the observation of declination at station No. 26, Mabushi in May 1951 was found to be unreliable due to the mismanagement.

In order to eliminate the geomagnetic daily variation and disturbances that may be assumed to be almost the same within a region of a few hundred *kilometers* in distance, Kakioka Magnetic Observatory is taken as the standard point. Furthermore, differences in general secular changes between Ooshima and Kakioka are taken into consideration. Those are not negligible in two years, i.e. 0.5 *minute* of arc westward in declination and -0.4 *minute* of arc in inclination while almost zero in horizontal intensity. The local anomalous changes in three geomagnetic

Table I.

Station, No. 14 Zoo

Lat.$=34°45'.2$ N Long.$=139°26'.5$ E

Date	Time (J.S.T.)	*D*	*I*	*H*
July 31, 1953	17^h20^m	$6°24'.3$ W	$48°18'.7$	30187γ
	18 11	25.4	18.8	30188
	18 54	24.1	20.1	—
	19 26	22.4	18.4	30187
	Mean	$6°24'.0$	$48°19'.0$	30187γ

5) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **31** (1953), 211.

Table II.

Station, No. 16 Senzu Primary School

Lat.=34°46′.6 N Long.=139°25′.3 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Aug. 1, 1953	00ʰ26ᵐ	5°25′.0 W	48°33′.0	30188γ
	00 46	25.8	33.7	30190
	02 06	25.0	33.3	—
	02 42	24.4	32.9	—
	Mean	5°25′.1	48°33′.2	30189γ

Table III.

Station, No. 19 Ooshima Meteorol. Station

Lat.=34°45′.8 N Log.=139°22′.6 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Aug. 3, 1953	17ʰ36ᵐ	6°20′.0 W	48° 7′.6	30041γ
	18 15	19.7	7.6	36
	20 16	19.1	7.1	—
	20 40	19.4	7.2	—
	Mean	6°19′.5	48° 7′.4	30038γ

Table IV.

Station, No. 24 Oomiya Park, Nomashi Village

Lat.=34°43′.8 N Long.=139°21′.5 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Sept. 19, 1953	20ʰ58ᵐ	—	47°21′.2	30683γ
	21 16	—	20.6	—
	21 40	—	21.5	30671
	Mean		47°21′.1	30677γ

Table V.

Station, No. 26 Mabushi

Lat. = 34°41′.3 N Long. = 139°23′.3 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Aug. 11, 1953	09^h44^m	5°28′.5 W	46°51′.5	31558γ
	10 15	31.5	53.8	31560
	10 59	32.6	54.2	—
	11 22	33.7	53.9	31562
	Mean	5°31′.6	46°53′.4	31560γ

Table VI.

Station, No. 37 Mr. Masaka's garden, Nomashi Village

Lat. = 34°43′.6 N Long. = 139°21′.5 E

Date	Time (J.S.T.)	*D*	*I*	*H*
July 30, 1953	08^h56^m	6°10′.5 W	47°21′.2	
	10 12	09.9	21.4	
	12 42	14.2	20.6	
	14 12	14.7	25.9	
	16 10	13.2	23.4	
	17 46	11.3	23.6	
	18 30	10.4	23.3	
	21 04	06.9	21.4	
	21 34	09.7	21.7	
July 31, 1953	07 05	07.8	21.7	
	07 53	08.8	22.7	29995γ
	09 18	09.9	21.9	29996
	10 10	—	21.5	29991
	10 52	10.2	20.7	29991
	11 36	11.4	22.0	29987
	Mean	6°10′.6	47°22′.0	29992γ

Table VII.

Station, No. 38 Yuba

Lat. = 34°45′.2 N Long. = 139°23′.9 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Aug. 3, 1953	11^h33^m	5° 5′.0 W	49° 22′.2	29004γ
	12 28	4.6	21.3	29013
	12 59	5.2	21.8	—
	13 26	5.1	21.5	29015
	Mean	5° 5′.0	49° 21′.7	29011γ

Table VIII.

Station, No. 39 Gojinka-chaya

Lat. = 34°44′.2 N Long. = 139°22′.9 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Aug. 2, 1953	13^h40^m	3° 58′.6 W	52° 14′.2	28514γ
	14 07	57.1	13.9	28530
	14 29	57.9	14.2	28522
	Mean	3° 57′.9	52° 14′.1	28522γ

Table IX.

Station, No. 40 Suberidai

Lat. = 34°42′.9 N Long. = 139°22′.5 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Aug. 12, 1953	18^h00^m	4° 6′.7 W	50° 40′.9	28977γ
	18 30	3.8	41.0	28967
	18 48	3.2	41.1	28968
	Mean	4° 4′.4	50° 41′.0	28971γ

Table X.

Station, No. 41 Sashikiji-Yokawa

Lat. = 34°41′.5 N Long. = 139°25′.6 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Sept. 19, 1953	$10^h 24^m$	8° 3′.3 W	48° 19′.3	31666γ
	10 58	2.8	19.3	31683
	11 27	3.3	20.3	—
	12 02	3.6	19.7	31666
	Mean	8° 3′.2	48° 19′.6	31672γ

Table XI.

Station, No. 42 Southern foot of Mt. Shiraishi

Lat. = 34°42′.3 N Long. = 139°24′.8 E

Date	Time (J.S.T.)	*D*	*I*	*H*
Aug. 2, 1953	$17^h 44^m$	4° 47′.3 W	47° 29′.5	32480γ
	18 08	48.7	29.7	32476
	18 30	47.7	29.6	32480
	19 12	48.2	30.5	32464
	Mean	4° 48′.0	47° 29′.8	32475γ

Table XII.

The local anomalous changes in geomagnetic components during the period from May 1951 to Aug. 1953.

Station	ΔD W	ΔY E	ΔH	ΔZ	ΔI
No. 14 Zoo	2′.1	−19γ	22γ	7γ	−0′.9
16 Senzu Prim. School	0.1	− 1	−41	−68	−1.1
19 Ooshima Meteorol. Station	0.5	− 4	8	−22	−1.6
24 Oomiya Park, Nomashi	—	—	−42	−21	1.3
26 Mabushi	—	—	−16	−36	−1.0
37 Mr. Masaka's garden	−3.5	32	−63	−63	0.3
38 Yuba	2.9	−25	17	−56	−3.8
39 Gojinka-chaya	3.7	−32	−41	−56	−0.1
40 Suberidai	−0.1	1	0	0	0.0
41 Sashikiji-Yokawa	−2.2	21	0	−42	−2.0

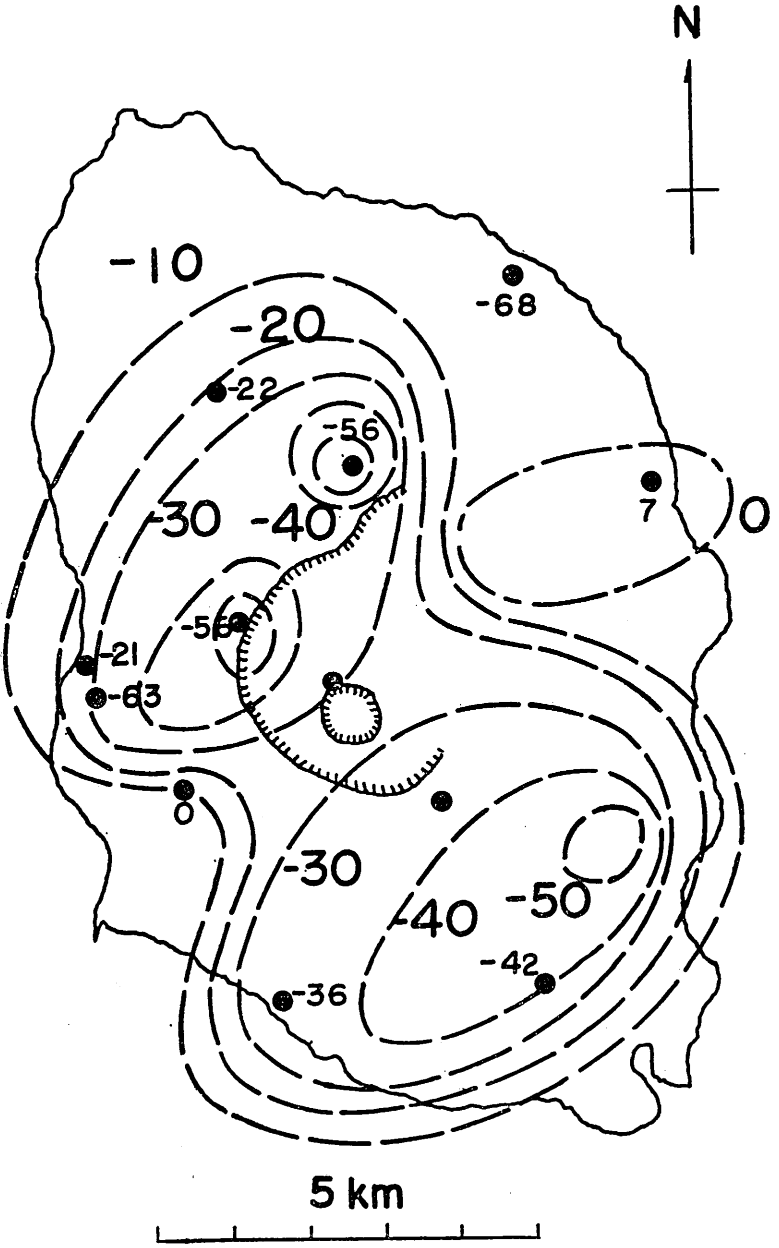

Fig. 1. The distribution of changes in vertical component during the period from May 1951 to Aug. 1953. The unit is *gamma*.

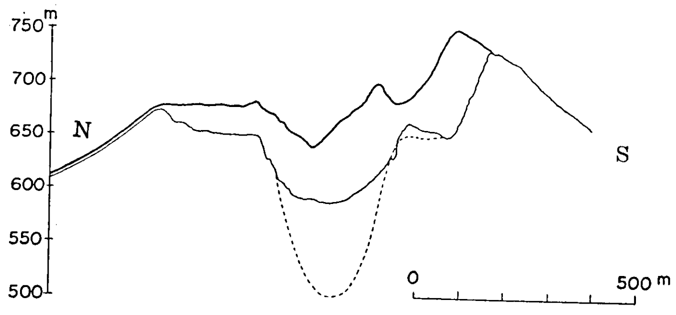

Fig. 2. Vertical section of the central cone.
—— 1951 (much the same as 1953)
—— 1950
········ 1940

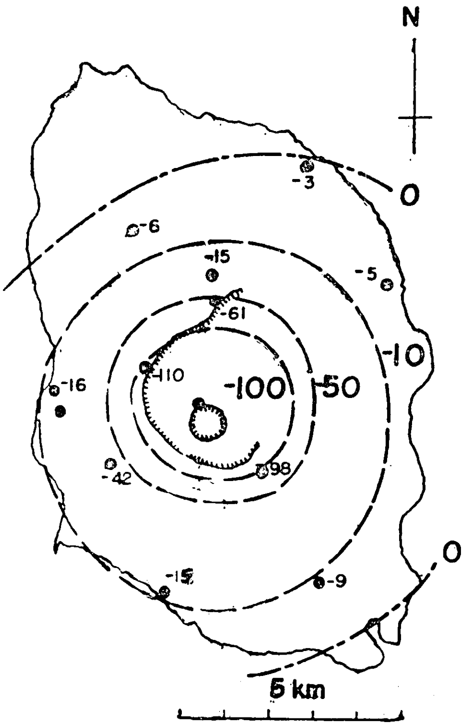

Fig. 3. The effect of ejected lava in the central cone upon the vertical component of the geomagnetic field. The unit is *gamma*.

elements thus corrected at the respective stations are shown in Table XII and Fig. 1 for the vertical component for example. The distribution of ΔZ in Fig. 1 seems to be roughly expressed with a superposed field of two magnetic dipoles.

In comparing the geomagnetic condition of the volcano in Aug. 1953 with that in May 1951, we have to pay attention to the fact that the upper part of the overflowed lava in the central cone was cooled in those two years and consequently got an intense magnetization. A large quantity of the ejected lava which amounts to about 7×10^7 *metric tons* causes some difficulties in presuming the changes in the internal state of the volcano (see Fig. 2). The effects of the lava which was magnetized during the abovementioned period upon the geomagnetic field are to be corrected on certain assumptions.

Judging from the fact that incandescent lava came in sight through the small fissure in the inner somma in Sept. 1952,[6] the lava in the central cone seems not to be cooled down so fast, some heat might have been supplied from the deeper part of the volcano. Though we have no convincing evidences concerning the distribution of temperature in the interior of the volcano, the writer assumes here that the upper part of the lava in the central cone had been cooled down below Curie point which is approximately at 600°C[7] during the said period. The part is shown between the contours in 1950 and 1951 in Fig. 2. Refering to the cooling curve of a fissure in the inner somma shown in Fig. 15 of the 4th paper, this assumption would be acceptable. According to the results of the experiments,[7] mean natural remanent magnetization of the ejected lava is about 0.05 *emu/cc*. The effects of the lava upon the geomagnetic field at each station are evaluated by Poisson's theorem of potential theory using the usual graphical method as was done in the case of dip-values in the 4th paper. The effects on the vertical component are shown in Fig. 3 for example.

The final values of local anomalous changes in three elements between 1951 and 1953 surveys both corrected in this way are shown in Table XIII and Figs. 4~6 in which the relation rot $\vec{H}=0$ was taken into consideration.

Table XIII.
The final values of local anomalous changes in three geomagnetic elements.

Station	ΔY	ΔX	ΔZ
No. 14 Zoo	−20γ	21γ	12γ
16 Senzu Prim. School	− 1	−44	−65
19 Ooshima Meteorol. Station	5	0	−16
24 Oomiya Park, Nomashi	—	−34	− 5
26 Mabushi	—	−35	−21
37 Mr. Masaka's garden	33	−55	−47
38 Yuba	−25	− 2	−41
39 Gojinka-chaya	−10	−55	54
40 Suberidai	− 8	15	42
41 Sashikiji-Yokawa	18	− 5	−33

6) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **32** (1954), 31.
7) T. NAGATA, *Journal of Geography* (*Tokyo*), **60** (1951), 44.

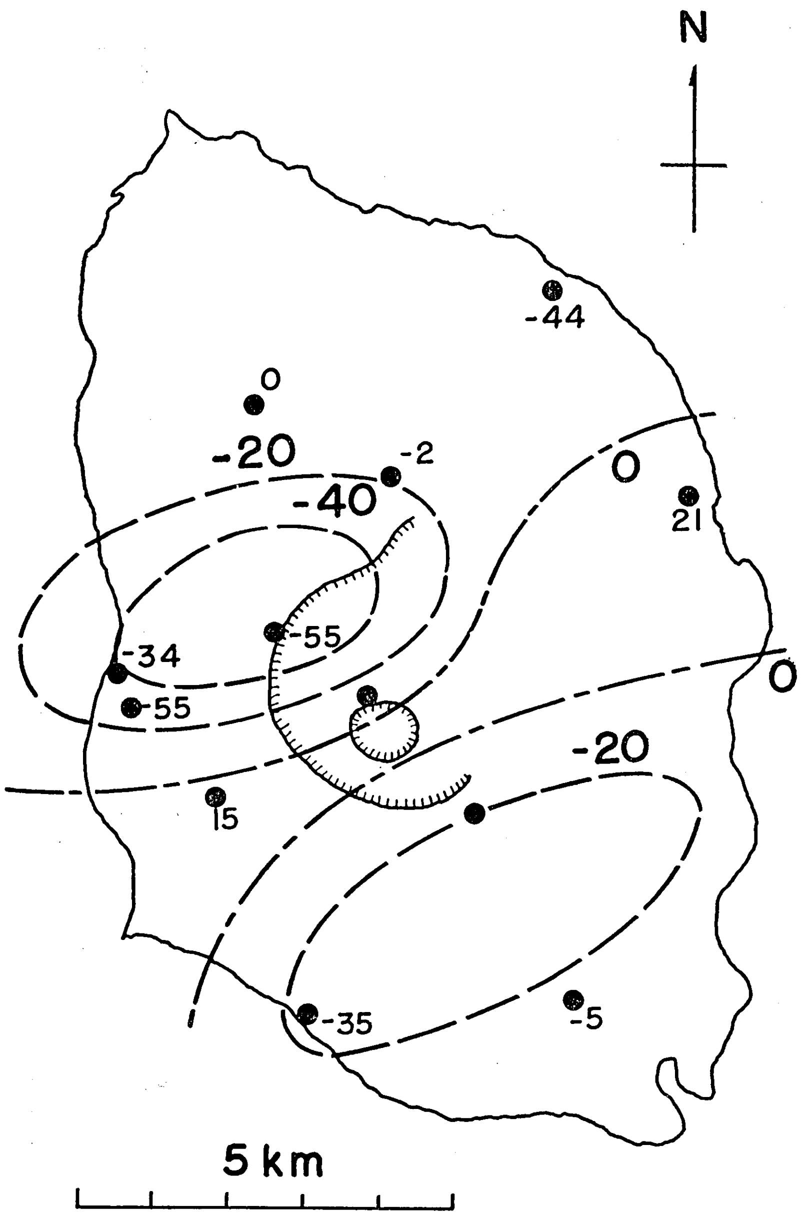

Fig. 4. The distribution of changes in geomagnetic north component. The unit is *gamma*.

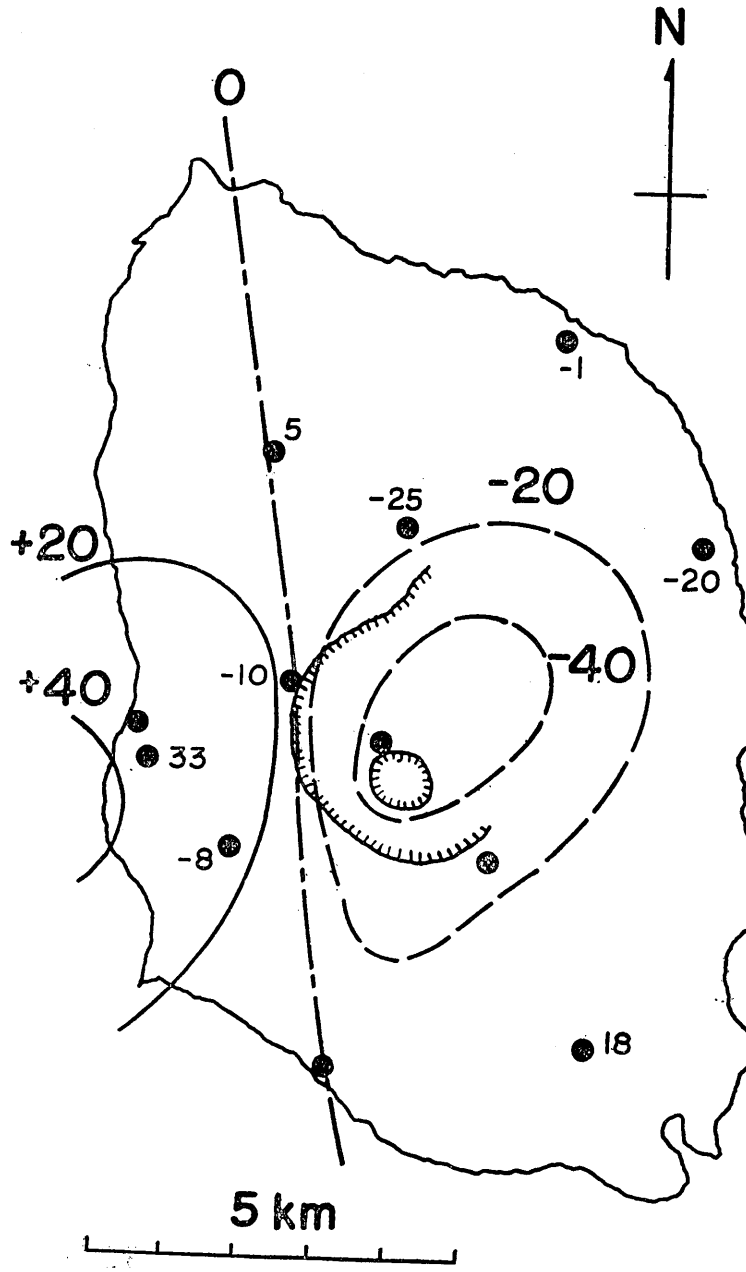

Fig. 5. The distribution of changes in geomagnetic east component. The unit is *gamma*.

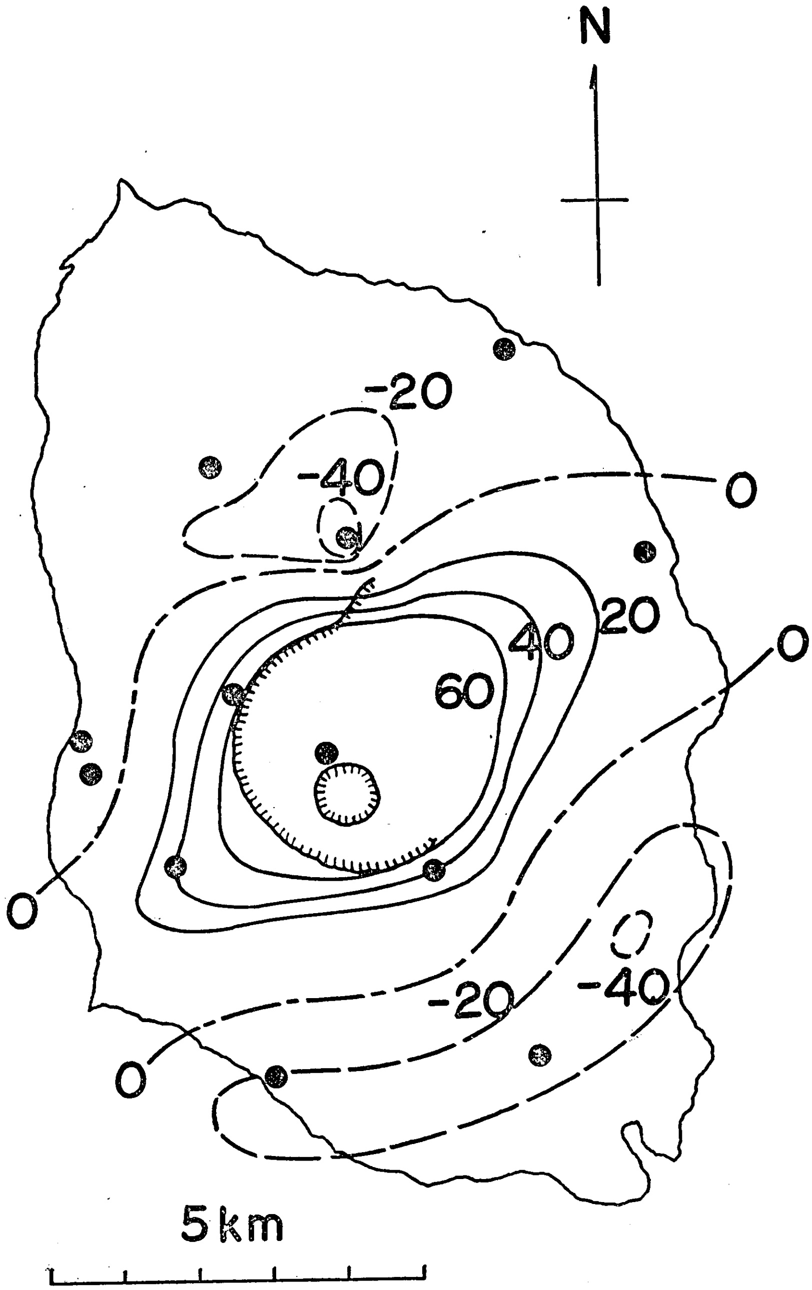

Fig. 6. The distribution of changes in vertical component. The unit is *gamma*.

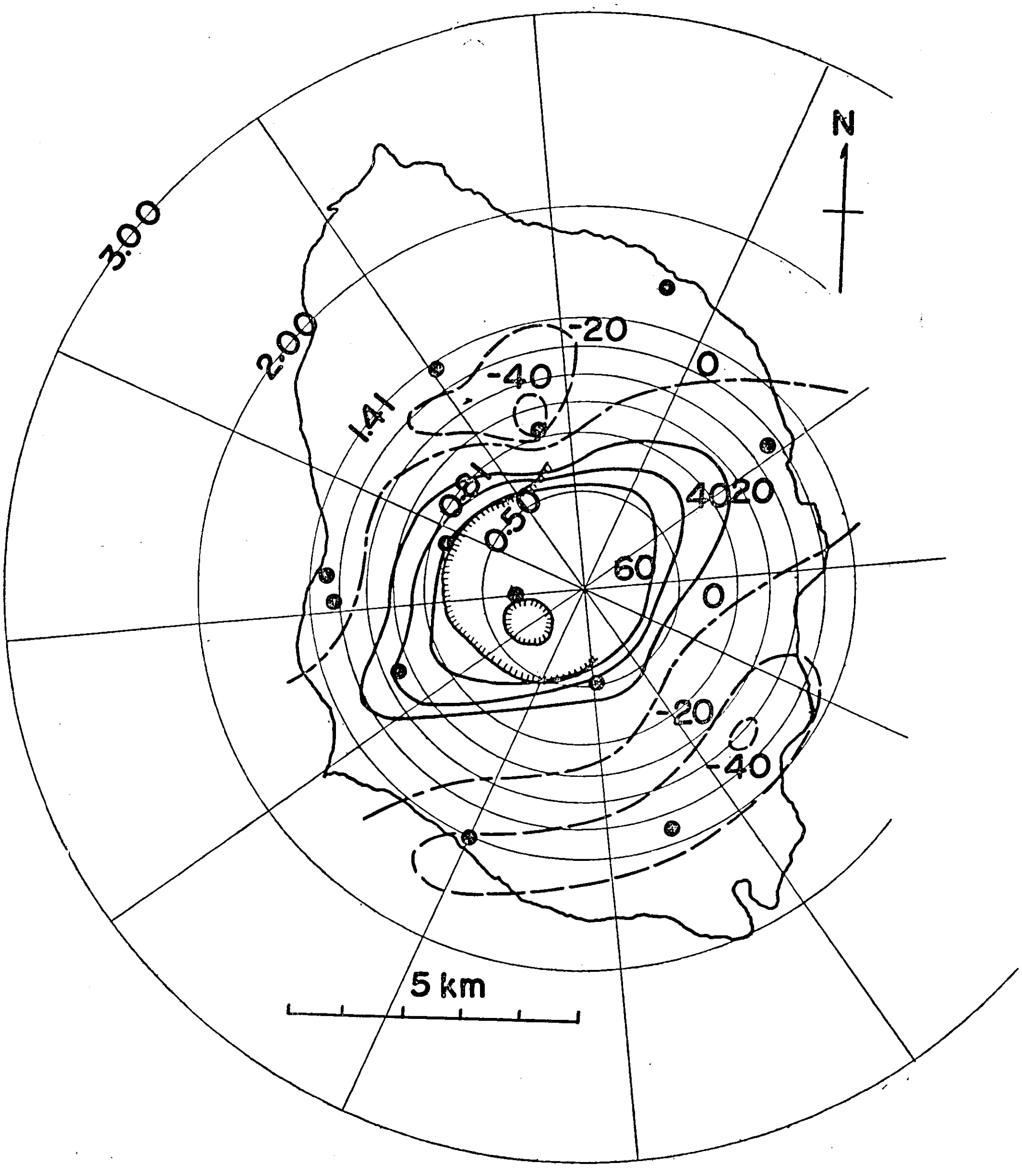

Fig. 7. Map of ΔZ distribution used in obtaining the coefficients A_{kn} and B_{kn}.

3. Determination of depth of sources.

In an analysis of the results obtained in the last section, the writer would like to take into consideration the fact that the height above sea-level is not the same for each station though it was usually ignored in all the previous analyses because of mathematical complexity. However, it will not be negligible because the difference between the highest and lowest stations amounts to 20∼30% of the supposed depth at where the changes in magnetization are occurring. The form of Volcano Mihara is expressed fairly well with a circular cone, the height and radius of which are respectively 800 *m* and 5 *km*. Then we assume that all stations are distributed on this circular cone and take the origin of cylindrical coordinates on its apex with positive z measured vertically downwards. With the aid of E. H. Vestine and N. Davids' method[8], an estimation of depth of sources responsible for the local anomalous changes of geomagnetic field is made as follows.

Denoting the magnetic potential of the local anomalous changes by ΔW and using Fourier series and Bessel functions, the solution of Laplace's equation becomes

$$\Delta W=\sum_{k=0}^{K}\sum_{n=0}^{N} e^{kz}[A_{kn}\cos n\phi+B_{kn}\sin n\phi]J_n(kr)\,, \qquad (1)$$

where k and n are positive integers, A_{kn} and B_{kn} are constants and $J_n(kr)$ is a Bessel function of the first kind. A special linear scale is adopted in which $10\,km=3$.

By differentiating (1), the components of intensity are obtained. Dropping summation signs, they become

$$\left.\begin{aligned}\Delta R&=-ke^{kz}[A_{kn}\cos n\phi+B_{kn}\sin n\phi]\Psi_n(kr)\,,\\ \Delta \Phi&=\ ne^{kz}\,[A_{kn}\sin n\phi-B_{kn}\cos n\phi]J_n(kr)/r\,,\\ \Delta Z&=-ke^{kz}[A_{kn}\cos n\phi+B_{kn}\sin n\phi]J_n(kr)\,,\end{aligned}\right\} \qquad (2)$$

where $\Psi_n(kr)=J_{n-1}(kr)-(n/kr)J_n(kr)\,.$

The coefficients A_{kn} and B_{kn} can be determined from any measured component of (2). For convenience' sake, the distribution of ΔZ is used here. At any point on the circular cone, we have

$$\left.\begin{aligned}&Z(z,r,\phi)=-ke^{kz}[A_{kn}\cos n\phi+B_{kn}\sin n\phi]J_n(kr)\,,\\ &z=r\frac{800}{5000}\,.\end{aligned}\right\} \qquad (3)$$

8) E. H. VESTINE and N. DAVIDS, *Terr. Mag.*, **50** (1945), 1.

In obtaining A_{kn} and B_{kn}, a set of five circles is drawn on a map of the ΔZ distribution so as to keep away from the central region of the volcano where the correction for the lava is very rough and the Fourier analysis for each circle afford five coefficients. By means of the method of least square, A_{kn} and B_{kn} are obtained as shown in Table XIV.

Applying these coefficients, ΔZ on the circular cone and ΔW on the various horizons both in the NS direction are calculated as shown in

Table XIV.

The values of A_{kn} and B_{kn}.

	n \ k	1	2	3	4	5
A_{kn}	0	5.32	-4.050×10^3	6.16	-8.75	-0.49
	1	1.723×10^3	-9.078×10^2	3.268×10^2	-7.853×10^1	6.78
	2	-2.964×10^4	7.370×10^3	-1.652×10^3	2.726×10^2	-18.75
	3	1.045×10^4	-1.108×10^4	1.123×10^3	-2.279×10^3	-15.17
	4	1.031×10^4	-2.508×10^2	-3.045×10^1	6.02	0.79
	5	7.911×10^4	2.327×10^3	-5.836×10^2	5.528×10^1	0.29
B_{kn}	1	-1.473×10^2	6.688×10^1	0.43	-5.29	5.92
	2	-4.106×10^4	1.010×10^4	-2.225×10^3	3.458×10^2	-20.37
	3	-1.882×10^5	1.899×10^4	-2.036×10^3	4.867×10^1	25.86
	4	2.890×10^2	-4.049×10^2	1.235×10^2	-2.452×10^1	2.49
	5	-1.742×10^5	-5.989×10^3	1.394×10^3	-1.215×10^2	-3.17

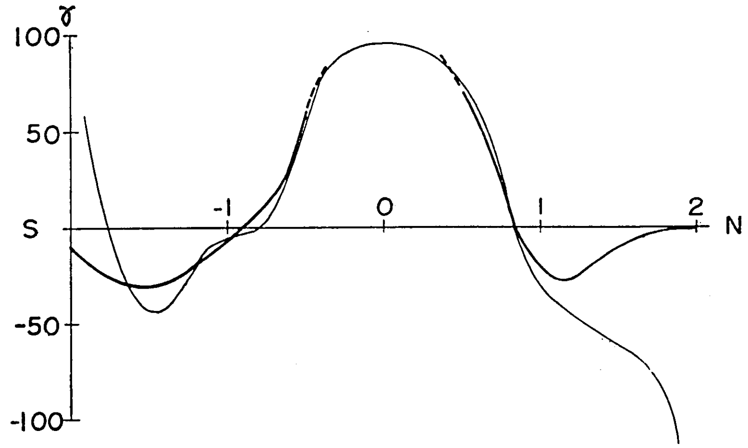

Fig. 8. ΔZ on the circular cone in the NS direction.
—— observed values —— calculated values

Figs. 8 and 9. In these figures, there are some discrepancies in distant parts from the origin. These may be ascribed to the extrapolation of the expression whose coefficients are determined with the values of inner region.

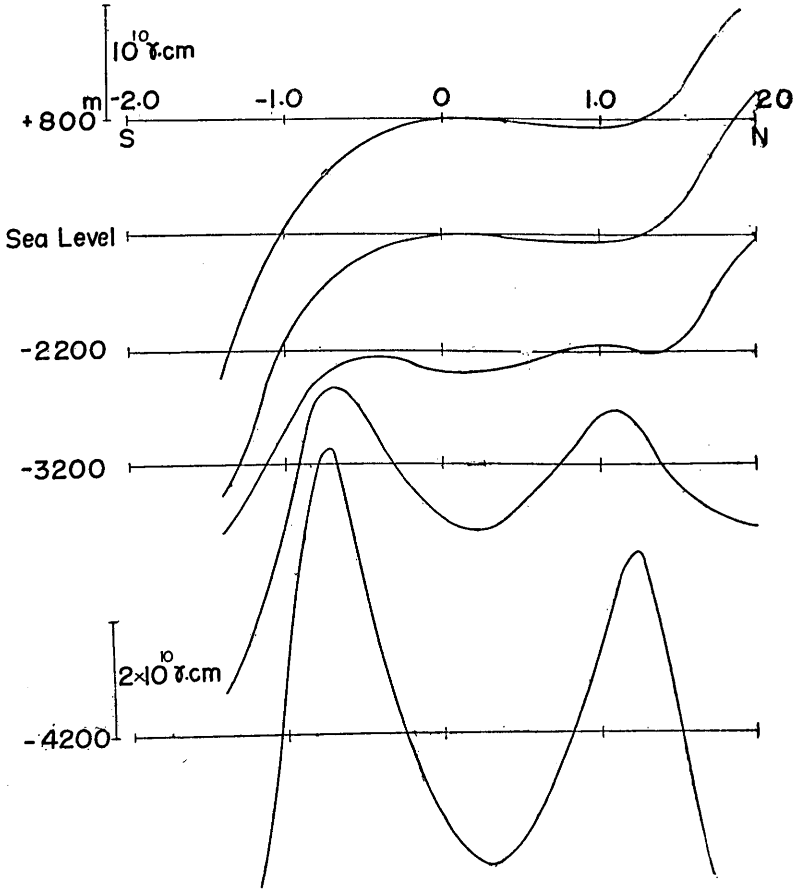

Fig. 9. ΔW on the various horizons in the NS direction.

Since the value of k is larger for the higher harmonics than the lower ones, the higher harmonics increase prominently as the source is approached, but never exceed materially the lower harmonics in amplitude unless the source has been reached. As may be seen in the figures, the distribution of ΔW at a depth less than $2200\,m$ are fairly convergent, while it seems more divergent according as the depth becomes great. Hence, we may assume that the sources are to be found at

2∼3 *km* depth from the sea-level.

4. Determination of a magnetic dipole.

In order to compare with the analyses of the 1950 survey in which T. Rikitake took a conventional dipole model, the position, intensity and direction of an underground magnetic dipole corresponding the magnetic changes on the earth's surface are determined with the aid of the method devised by Rikitake.[9)]

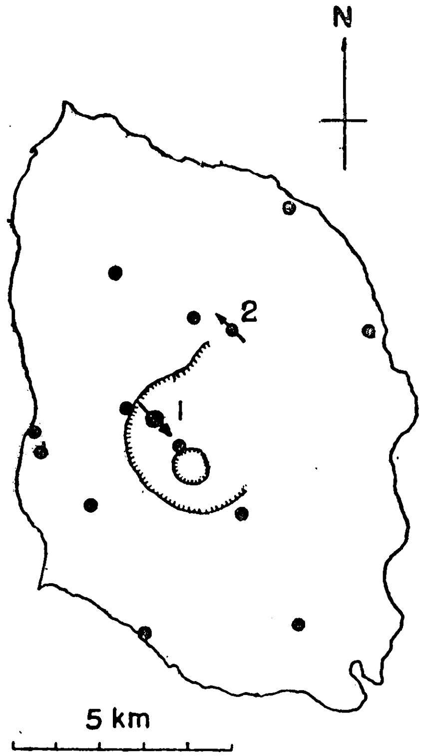

Fig. 10. The directions and positions of the magnetic dipoles corresponding to the changes in geomagnetic field.
1: July—Sept. 1950.
2: May 1951—Aug. 1953.

The distributions of geomagnetic components are expressed in the next form

$$\left.\begin{aligned}\Delta X &= A_1 + B_1x + C_1y + D_1x^2 \\ &\quad + E_1xy + F_1y^2 + G_1x^3 \\ &\quad + H_1x^2y + I_1xy^2 + J_1y^3\,, \\ \Delta Y &= A_2 + B_2x + C_2y + \cdots \\ &\quad \cdots\cdots\cdots\cdots \\ &\quad \cdots\cdots\cdots\cdots\,, \\ \Delta Z &= A_3 + B_3x + C_3y + \cdots \\ &\quad \cdots\cdots\cdots\cdots \\ &\quad \cdots\cdots\cdots\cdots\,,\end{aligned}\right\} \tag{4}$$

where the origin is taken at that of the cylindrical coordinates in the last section. Using the values of three components at ten points, the constants $A_1, B_1, C_1, \cdots\cdots,$ $A_2, B_2, C_2, \cdots\cdots,$ $A_3, B_3, C_3, \cdots\cdots$ are determined by means of the method of least squares.

The coefficients of spherical harmonic expansion of magnetic potential on a sphere of radius a are obtained by solving certain simultaneous equations which contain the constants $A_1, B_1, C_1, \cdots\cdots, A_2, B_2, C_2, \cdots\cdots, A_3, B_3, C_3, \cdots\cdots$. Then adjusting a so as to minimize the square sum of the second degree coefficients, the depth of the magnetic centre is determined to be 4.7 *km*,

9) T. Rikitake, *Journ. Geomagn. Geoelectr.*, **2** (1950), 20 and 25.

while the position is also obtained as shown in Fig. 10. The obtained quantities are tabulated in Table XV. Table XVI shows all the results obtained by Rikitake and the writer concerning the magnetic centre corresponding the local anomalous changes in Ooshima by now. The remarkable changes observed in Sept. 1950 seem to have recovered about one tenth by Aug. 1953 though the changes between the period from Sept. 1950 to May 1951 are not clear. This result may harmonize with the fact that the minor activities took place in Oct. 1953 and afterwards. The volcano seems still active though we got a geomagnetic change in an opposite sense to that occured in 1950. In Table XVI, the directions of magnetization and demagnetization of the underground dipoles deviate from the geomagnetic north as much as 45 *degrees*. If it is so, we might expect some other causes for the geomagnetic changes because the direction should agree with that of the general field there provided we only consider simple magnetization and demagnetization associated with rises and falls of volcanic activity. But the writer can say nothing about another causes at the moment. Many further observations would be needed for any discussions along this line.

Table XV.

The coefficients of spherical harmonic expansions and determined quantities.

Coef.	a_1^0	a_1^1	b_1^1	a_2^0	a_2^1	b_2^1	a_2^2	b_2^2
Value	0.8	−54.9	−61.5	0.3	16.7	20.9	0.8	2.1 γ
	$x=2.7\,km$,		$y=-0.1\,km$,		$z=4.7\,km$			

Table XVI.

The determined magnetic dipoles corresponding to the changes during various periods in Ooshima.

Period	Depth of centre	Azimuth of north seeking end	Dip of dipole	Magnetic moment
1936—1951	6.1 *km*	N 18°W	−17°	2.8×10^{15} *emu*
July—Sept. 1950	5.5 *km*	S 42°E	−63°	6.3×10^{14} *emu*
May 1951— Aug. 1953	4.7 *km*	N 48°W	88°	8.6×10^{13} *emu*

5. Summary and conclusion.

Analyzing the geomagnetic data obtained in May 1951 and Aug. 1953, the writer abstracted the local anomalous changes in geomagnetic components during this period. The effects of the lava cooled down on the surface was eliminated under certain assumptions. Using the distribution of ΔZ, an estimation of depth of sources was made by seeking the point where the solution of the magnetic potential becomes divergent. Thus upper limit of the sources was found to be about $2\sim3$ *km* beneath the volcano.

With the aid of Rikitake's method, the depth of the magnetic centre is also determined to be 4.7 *km* using the partial derivatives of distributions of ΔX, ΔY and ΔZ.

Judging from the results and associated analyses of the geomagnetic studies, it is likely that the activity of the volcano which gave rise to a great change in the earth's magnetic field in 1950 is still continuing though a part of the change has been recovering during the period from 1951 to 1953. Although the main part of volcanic geomagnetic change would be closely related to the thermal condition in the interior of volcanoes, simple considerations concerning magnetization and demagnetization are not enough to explain rather complicated features of the changes observed on Volcano Mihara. Further observations should be made in order to study in detail.

In concluding, the writer wishes to express his sincerest thanks to Dr. T. Rikitake who advised and encouraged the writer from England throughout the course of this study. To Prof. T. Nagata for his helpful criticisms, the writer's cordial thanks are also due. Mr. A. Okada assisted the writer in field works, to whom the writer's hearty thanks are also due. The writer also acknowledges the facilities given by Tokai Kisen Company in magnetic surveys.

12. 三原山の地球磁気学的研究
第 5 報
(1951年5月から1953年8月にいたる期間の地磁気三成分の変化)

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第 3 報において報告したように，1951 年 5 月地理調査所型磁気儀を用いて，大島全島 10 点について地磁気三成分の最高度の精密測定を行つた．以来 2 年余，三原山は外見的には一応静穏に返つたようであつた．この間における一連の伏角測量と，地磁気偏角の連続観測との結果は第 4 報で報告した．これらの観測結果を更に確めるために，1953 年 8 月再測を行い，この 2 年間における局地的異常変化を求めた．この際地磁気日変化及び擾乱ならびに永年変化の影響を除去し，又，地下の状態変化を推論するために，この二回の観測の間に冷却したであろうと考えられる噴出熔岩の一部が地球磁場に及ぼす効果を計算して，これを補正した．この際，火口内の熔岩の幾何の深さまでが Curie 点以下に冷却したかが問題である．この評価はなるべく慎重に行つたつもりであるが，今後も注目すべき現象の一つと思われる．

この地磁気の異常変化の源を推算するために，E. H. Vestine-N. Davids の方法を用い，測点が必ずしも同一平面上にないことを考慮すると，大体，源の上限は海面下 2〜3 km となる．

力武の方法を用いて磁気異常中心の深さを求めると，約 4.7 km となり，前記結果とも矛盾しない．又，新たに生じた帯磁の方向及び磁気能率等は第 1 報から第 4 報にいたる総ての結果と調和する．