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Analysis of the Variation of Geomagnetic Total Force at the Kusatsu-Shirane Volcano: The Remarkable Changes in the Geomagnetic Total Force in 1990 and the Estimated Thermal Demagnetization Model

by

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Abstract

Repeat measurements of the geomagnetic total force at the Kusatsu-Shirane volcano using a proton-precession magnetometer have been carried out nearly every year since 1976 by the Kakioka Magnetic Observatory. During a measurement in September, 1990, remarkable changes in the geomagnetic total force were observed. The maximum change value during one year amounted to −11.1 nT at the No. 5 observation point located southeast from Yugama. Increases of total force were observed at the northern area of Yugama, and decreases at the southern area. Such changes can be explained by a demagnetization of the material under the volcano. On the other hand, volcanic earthquakes and volcanic tremors have occurred frequently since February, 1990. Further, geochemical data have indicated a high level of volcanic activities. It is inferred that the geomagnetic total force changes are caused by the thermal demagnetization of the rocks under the vicinity of Yugama. By the use of the least squares method, we have proposed two thermal demagnetization models and found that the estimated demagnetized area almost coincided with the focuses of volcanic earthquakes. These results imply that geomagnetic observation is a useful method for understanding volcanic activities at the Kusatsu-Shirane volcano and many other andesitic volcanoes.

1. Introduction

Recently remarkable changes in the geomagnetic total force in association with volcanic activities have been reported on some volcanoes in Japan, such as Izu-Oshima Island, Miyakejima Island (e.g., Yukutake et al., 1990; Nakagawa et al., 1994). Because these volcanoes are composed mainly of basaltic rocks containing a great deal of magnetite, they have advantages for detection of magnetic changes associated with volcanic activities. On the other hand, in case of andesitic volcanoes, it was supposed that the magnetic changes might be small, so that it would be difficult to detect it. However, since most volcanoes in Japan are composed of andesitic rocks, it is important to research these volcanoes for prediction of volcanic eruptions.

The Kakioka Magnetic Observatory and its branches have continued magnetic total force observation for research on volcanic eruptions at Sakura-jima and Aso (by Kanoya Magnetic Observatory), Kusatsu-Shirane, Unzen and Miyake-jima (by Kakioka Magnetic Observatory), Meakan-dake (by Memanbetsu Magnetic Observatory).

At the Kusatsu-Shirane volcano, repeat measurements of geomagnetic total force have been carried out nearly every year since 1976. The Kusatsu-Shirane volcano is a stratovolcano composed of andesitic rocks located at the northwest part of Gunma Prefecture in the central part of Japan. The volcano is an active volcano, which has often caused small eruptions in historical time. Recently, small vapor explosions occurred at Mizugama crater lake in 1976 and at Yugama crater lake in 1982-1984. Some total force changes were reported in relation to the eruption in 1982-1984 (Ohchi, 1987). As the changing patterns of total force were decreases at the southern area of Yugama and increases at the northern area, this event has been interpreted as the occurrence of a thermal demagnetization under Yugama.

In this paper, we mainly report a remarkable change of the geomagnetic total force that occurred in the period of 1989 to 1990, and discuss the thermal demagnetization models under the volcano. We also report the characteristics of long-term variations in the vicinity of the Kusatsu-Shirane volcano.

2. Observations

As Ohchi (1987) has described the observations in detail, here we explain them briefly.

The locations of the Kusatsu-Shirane volcano (KST), Yatsugatake Magnetic Observatory (YAT), Kakioka Magnetic Observatory (KAK) and points of repeated total force observation are shown in Fig. 1. Most of the repeat observation points, which amount to 17 points, are located around Yugama (YGM), which is a crater lake located near the summit of Kusatsu-Shirane volcano.

Repeated observations have been conducted periodically once a year, usually in September or October. To reduce the effect of seasonal variations, we have made the observation at a fixed season. A portable proton magnetometer

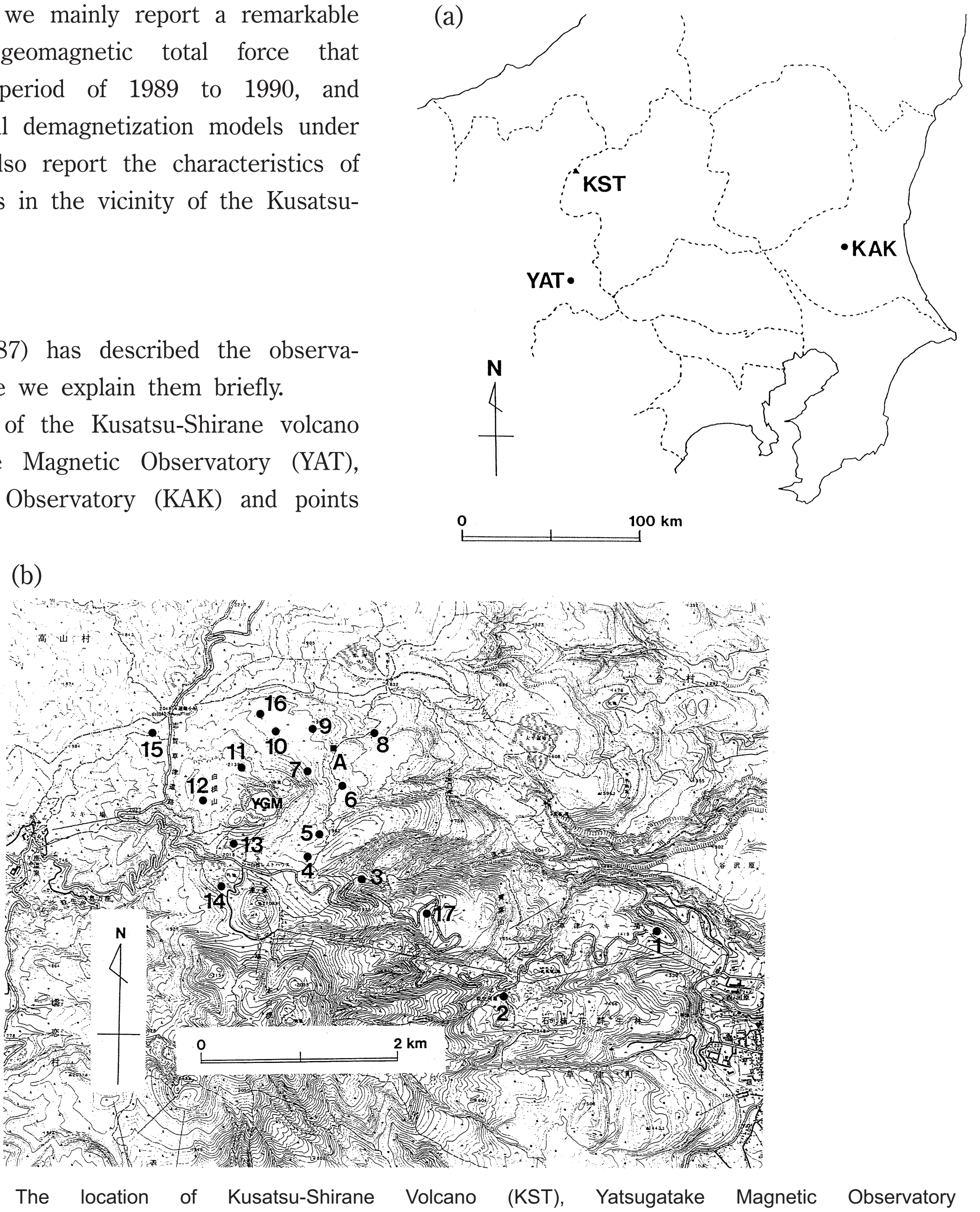


Fig. 1 (a) The location of Kusatsu-Shirane Volcano (KST), Yatsugatake Magnetic Observatory belongs to the Earthquake Research Institute of the University of Tokyo (YAT) and Kakioka Magnetic Observatory (KAK).
(b) Distribution of repeat observation points (Nos. 1 ∼ 17)
A: the observation point of volcanic earthquakes by JMA
YGM: Yugama crater lake

(G816, Geometrics Co., Ltd.) has been used for the repeat observations. The measurement height of the proton sensor from the ground level is 1.4 m. In parallel with this measurement, we have been conducting 2.0 m height measurement from 1988 to check very local abnormal magnetic changes caused by environmental changes near the observation points, such as moving stones. One minute value has been taken at a temporary reference station during the period of repeat observations for reduction of the time variations of the external magnetic field, such as daily variations. This temporary reference station has been installed every time that the repeated observations were made. From 1985, the site of the station has been located near the No. 5 repeat point.

The obtained total force data at each repeat point have been corrected by the reference station, and then they have been transferred to the values of a datum point of YAT, which is located about 60 km southward from the Kusatsu-Shirane volcano. The procedure of the calculation is described as

$$F_{KST\text{-}YAT}=(F_{OBS}\text{-}F_{REF})_{MSR}+(F_{REF}\text{-}F_{YAT})_{AV},$$

where $(F_{OBS}\text{-}F_{REF})_{MSR}$ is the difference of the total force between the repeat point and the reference station obtained by a 10-minute measurement. $(F_{REF}\text{-}F_{YAT})_{AV}$ is the difference between the reference station and YAT obtained by averaging nighttime data using a few magnetic calm days.

The results of the repeated observations from 1976 at the Kusatsu-Shirane volcano are shown in Fig. 2. The figure also shows month-to-month variations of the number of volcanic earthquakes observed by the Japan Meteorological Agency (JMA) at point A.

3. Characteristics of the long-term variation of total force around the Kusatsu-Shirane volcano

In this section we review the results of repeated observations starting from 1976 at the Kusatsu-Shirane volcano, and discuss the long-term variation in relation with volcanic activities.

The long-term variation of the total force around a volcano is considered to imply a status change of the volcano. For instance, when the temperature beneath the volcano rises, the distribution of total force changes will show a demagnetization pattern. On the contrary, the distribution will show a magnetization pattern when the temperature goes down. In case a hot zone beneath the volcano moves to a lateral direction, the distribution will move to the same direction.

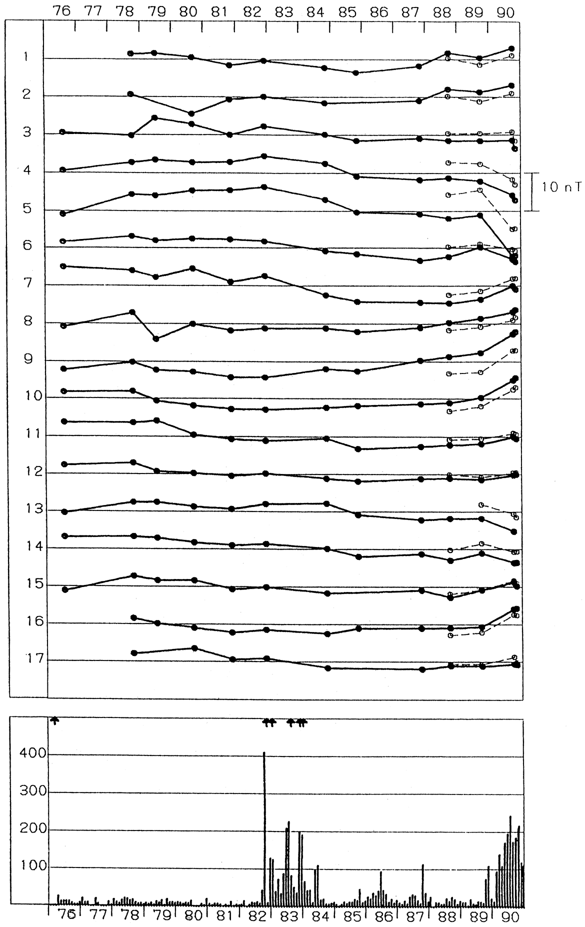


Fig. 2 Solid line: Variations of the geomagnetic total force relative to that at YAT (sensor height=1.4m). Broken line: Variations at sensor height=2.0m Lower shows month-to-month variations of the number of volcanic earthquakes observed by JMA at point A. Arrows show the occurrence of the eruptions.

However, there are many origins of long-term variations other than volcanic origin, so that the interpretation should be done carefully to distinguish volcanic origin. The long-term variations of an observation point may be caused by the following reasons:

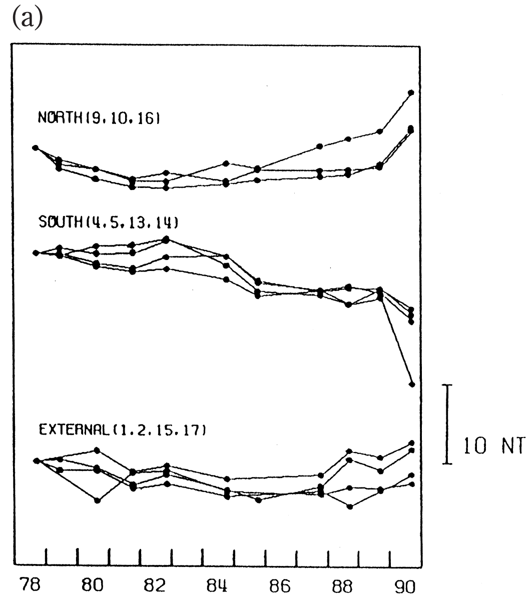
1) Variations caused by volcanic activities
2) Regional secular variations around the Kusatsu-Shirane volcano caused by the crust or the core origin
3) Secular variations of the base station of YAT
4) Environmental changes around the observation point caused by artificial or natural reasons
5) Correction errors of the time variation of magnetic field
6) Measurement errors.

Generally, it is not so easy to separate the variations caused by the above-mentioned 1) reason from the others. However, we can distinguish the 2) and 3) reasons from the others, because those effects are nearly the same at all observation points. Also we can minimize the effects of the 4), 5), and 6) reasons by careful measurement and maintenance around the observation points. And when the distribution of long-term variation shows a clear demagnetization or magnetization pattern, then we can regard it as caused by the 1) reason.

Here we show the long-term variations in Fig. 3 (a) as classified into the northern site of Yugama (NORTH: Nos. 9, 10, 16), the southern site of Yugama (SOUTH: Nos. 4, 5, 13, 14) and a site remote from Yugama (EXTERNAL: Nos. 1, 2, 15, 17). The datum year of the plot in the figure is 1978. The estimated changes in the total force at the EXTERNAL are evaluated to be small even if a large demagnetization occurs under the Yugama. It is found that the long-term variations which belong to the same group are quite similar, and the groups of the NORTH and the SOUTH show a well-reversed correlation.

Simple average values of each grouped long-term variation and a secular variation of KAK relative to YAT (KAK-YAT) are shown in Fig. 3 (b). Here the value of KAK-YAT has been obtained from midnight data of geomagnetic quiet days.

Since four observation points which belong to the EXTERNAL are located far from Yugama, the magnetic changes associated with volcanic activities around Yugama are estimated to be very small. And also since the trends of long-term variations of these points are similar in spite of being located several km's distance from each other, their long-term variations should be regarded as a regional secular variation around the



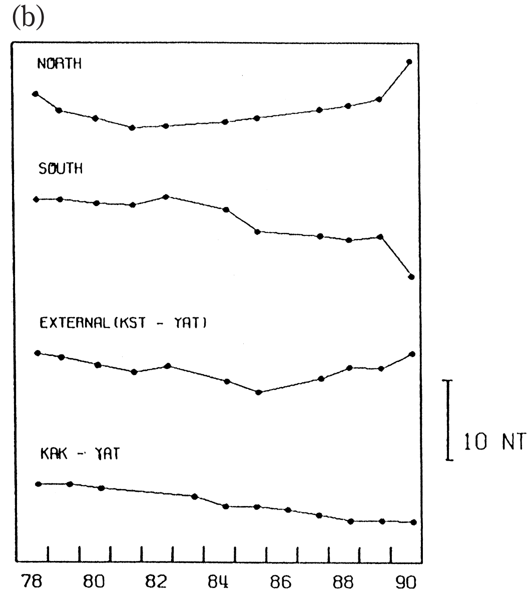


Fig. 3 (a) Long-term variation at the grouped observation points (NORTH, SOUTH and EXTERNAL). The numbers in the figure are the station numbers in Fig. 1 (b).
(b) Long-term variation of averages at the NORTH, SOUTH and EXTERNAL observation points and secular variation at KAK relative to YAT.

Kusatsu-Shirane volcano. Although there is a possibility that this secular variation has been caused by that of YAT, we infer that the variation is mainly caused around the Kusatsu-Shirane volcano, judging from the features of the trend of KAK-YAT.

The trend of the secular variation around the Kusatsu-Shirane volcano had been decreasing until 1985; afterwards it changed to increasing after 1985. Ohchi (1987) has pointed out that the decreasing trend up to 1985 is interpreted by the global trend of secular variation around the central part of Japan. As for the increasing trend since 1985, we suppose it is a crustal-originated variation from a wide area around the volcano.

One of the supposed origins of the secular variation is a piezomagnetic field caused by a distribution change of the regional stress field around the Kusatsu-Shirane volcano. An extension of the thermal demagnetization zone in the crust or getting the magnetization by cooling rocks deep underground is also to be supposed. Yukutake et al. (1990) have examined a secular variation of total force during the period of 1968 to 1987 at NOM in Oshima Island. An abnormal decrease of secular change in total force at NOM until 1978 was found by comparison with Kakioka (KAK), Kanozan (KNZ) and Hachijojima (HJJ) magnetic observatories. The decreasing rate of the anomalous change was estimated to be −1.3 nT/year. After that, it has returned to a normal trend since 1980. This abnormal secular variation was considered a regional secular variation spreading over the entire Oshima Island, because the same changes were observed at other stations in the island, not limited to NOM. They have been interpreted that the anomalous change was caused by tectonic activities between the Izu Peninsula and Oshima Island. For the case of the Kusatsu-Shirane volcano, there is a possibility that the secular change implies tectonic activities around the volcano. Although this phenomenon is very interesting, in this paper we will mainly discuss the thermal demagnetization which has occurred.

To make clear the magnetic changes related to volcanic activities, the regional secular variation should be eliminated. The long-term variations at the NORTH and the SOUTH eliminated regional secular variations (EXTERNAL) are shown in Fig. 4. Then the reverse correlation between the NORTH and the SOUTH becomes clear. If we assume the long-term variations of the NORTH and the SOUTH indicate the thermal status beneath the volcano, it can be said that the temperature underneath the volcano had been cooling down before 1982, and it has changed to a rising trend after that year. Here we notice that several vapor explosions occurred at Yugama around 1982-1984. The coincidence of the explosions and the changing of long-term variations may imply that the explosions became a trigger to the temperature's rising beneath the volcano.

The amount of regional secular variation (EXTERNAL) from September 1989 to September 1990 has been estimated to be +1.8 nT.

4. Remarkable changes in geomagnetic total force during one year from 1989 to 1990

Remarkable changes in geomagnetic total force were found by the repeat observation conducted in September 1990 (Fig. 5, Table 1). The distribution of total force showed a typical demagnetization pattern, which is increasing at the northern part and decreasing at the southern part of Yugama. The maximum decreased value at the southern area reached −11.1 nT at the No. 5 observation point. We confirmed the validity of the result by conducting re-observation in October 1990 (Table 1).

On the other hand, the seismic activities of

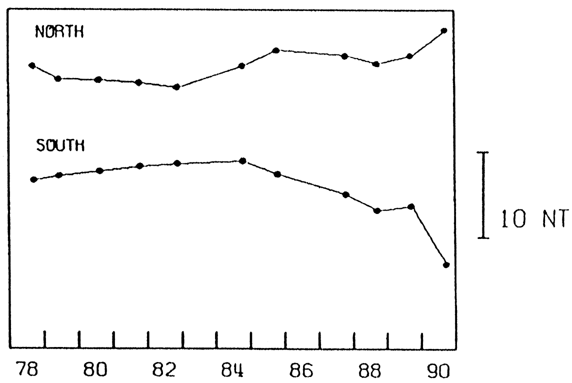


Fig. 4 Long-term variation at NORTH and SOUTH corrected by the secular variation at EXTERNAL.

the volcano changed to a high level suddenly in February 1990, and then they became more active with occasionally-occurring volcanic tremors (JMA, 1990). The seismic activities of this time exceeded the activities in the period of 1982-1984 when vapor explosions occurred. During the same time, the Kusatsu-Shirane Volcano Observatory of Tokyo Institute of Technology (1990) reported a drop of concentration of hydrogen sulfide existing in the volcanic gas which was sampled at the gas emission zone located in the northern part of Yugama. Since the drop of concentration of hydrogen sulfide was observed at both of the previous vapor explosions in 1976 and in 1982-1984, it has been thought to be an indicator of volcanic activities. Furthermore, during the same time, a different color zone appeared on the surface of the Yugama crater lake, and a hydrophone observation detected vapor jet signals frequently from the bottom of Yugama.

It can generally be said that the volcanic activities under the ground of the Kusatsu-Shirane volcano in 1990, as inferred from seismicity, geochemical and geomagnetic aspects, was at a very high level, although the volcano did not make any eruptions.

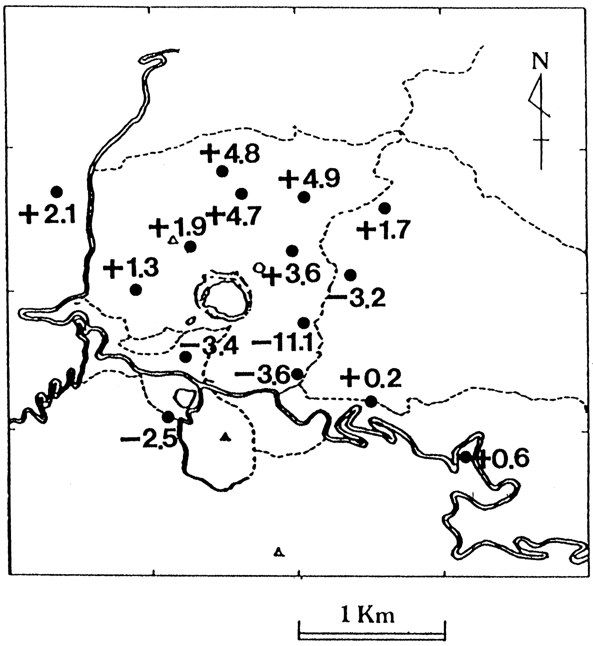


Fig. 5 Changes in the geomagnetic total force from Sep. 1989 to Sep. 1990 (unit in nT).

Table 1 Results of the observation in Sep. 1989 (1), Sep. 1990 (2) and Oct. 1990 (3) (relative to YAT, unit in nT).

NO.	(1) 1989.9	(2) 1990.9	(3) 1990.10	(2)-(1)	(3)-(2)
1	405.0	407.7	—	2.7	—
2	49.5	51.4	—	1.9	—
3	958.4	958.6	956.4	0.2	-2.2
4	438.0	434.4	433.1	-3.6	-1.3
5	761.9	750.8	751.0	-11.1	0.2
6	434.9	431.7	431.1	-3.2	-0.6
7	370.1	373.7	372.8	3.6	-0.9
8	267.1	268.8	269.4	1.7	0.6
9	812.5	817.4	818.0	4.9	0.6
10	727.9	732.6	733.3	4.7	0.7
11	464.6	466.5	466.0	1.9	-0.5
12	499.2	500.5	500.7	1.3	0.2
13	-139.0	-142.4	—	-3.4	—
14	278.7	276.2	276.3	-2.5	0.1
15	373.3	375.4	374.4	2.1	1.0
16	572.6	577.4	577.6	4.8	0.2
17	677.6	678.2	678.1	0.6	-0.1

5. Thermal demagnetization model

Some sources have been considered as origins of magnetic changes related to volcanic activities, such as thermal demagnetization and a piezomagnetic field with stress change and topographic deformation. The distribution of the change of total force during the interval from Sep. 1989 to Sep. 1990 observed at the Kusatsu-Shirane volcano showed a typical thermal demagnetization pattern, so that we have estimated the position and the magnitude of the thermal demagnetized zone.

A thermal demagnetization dipole model (model A) which is obtained by total force changes of the Nos. 3 to 17 observation points using the least square method is shown in Fig. 6. In this estimation, we used +1.8 nT as a correction value for secular variation, as mentioned in section 3. Also we assumed that the direction of the remanent magnetization of the Kusatsu-Shirane volcano coincided with the present magnetic field. The horizontal position of the estimated dipole is just at Mizugama, which is located 350 m northeast from the center of Yugama, while the depth is 900 m (the elevation is 1140 m above sea level), and the magnitude is 5.3×10^7 A・m^2. If we assume the average magnetization of the volcano is 1.0 A/m (1.0×10^{-3} emu/cc), the dipole model is equivalent to a perfect demagnetized sphere, of which the radius is 230 m. As a first approximation, it can be said that the dipole model gives a good agreement with observational results. However, the detailed differences between observed and calculated results exceeded ±2 nT at 7 observation points.

Generally, a magnetic change at the surface caused by a demagnetization which occurred deep enough underground must be represented by a dipole moment. This means that the shape of the demagnetized zone does not have as much of an influence as the magnetic changes at the surface. From this point of view, the disagreement between observed and calculated values in model A can not be explained by a deep demagnetized source. It may be caused by occurrence of a partially shallow demagnetization.

Another dipole model, Model B, shown in Fig. 7, which has been obtained without using data of Nos. 13 and 14, shows a good coincidence of observations and calculated results. Model B is located 600 m ENE from the center of Yugama, while the depth is 550 m (the elevation is 1430 m above sea level), and the magnitude is 1.8×10^7 A・m². The radius of an equivalent demagnetized sphere is 160 m. The demagnetized volume is a third as much as the Model A. However, since we ignored the data of Nos. 13 and 14 to get this model, some new thermal demagnetized zone should be added beneath these points to explain their changes.

A distribution of the focuses of volcanic earthquakes by the Earthquake Research Institute (1990) is shown in Fig. 8. As shown in the figure, the Model A has a good coincidence with the distribution of the focuses of the earthquakes. For the Model B, both the horizontal position and depth are slightly different. The coincidence of the focuses of volcanic earthquakes and the thermal demagnetized zone can be explained as the following processes: Earthquakes make cracks, the cracks cause penetration or spreading of the hydrothermal system, and the spreading of the hydrothermal system causes the thermal demagnetization. But earthquakes may not happen at the shallow zone around the summit area which is covered by thick unconsolidated volcanic pyroclastic sediments, so that we cannot deny Model B in spite of its disagreement with the focuses.

Two types of heating processes under the

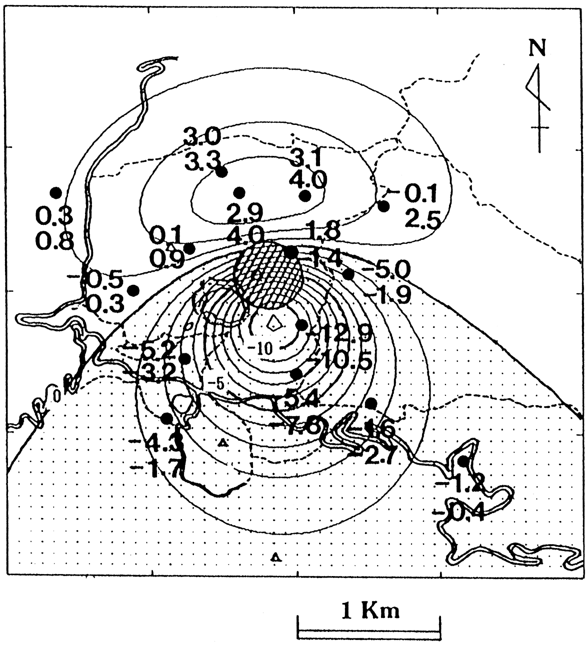


Fig. 6 Dipole model of thermal demagnetization (model A). The upper values at each observation point are the observed values corrected by secular variation, and the lower values are the calculated values. The depth of the dipole is about 900m. The contour interval is 1 nT, and the negative area is shaded. Contour values are at the height of 2000m from the sea level.

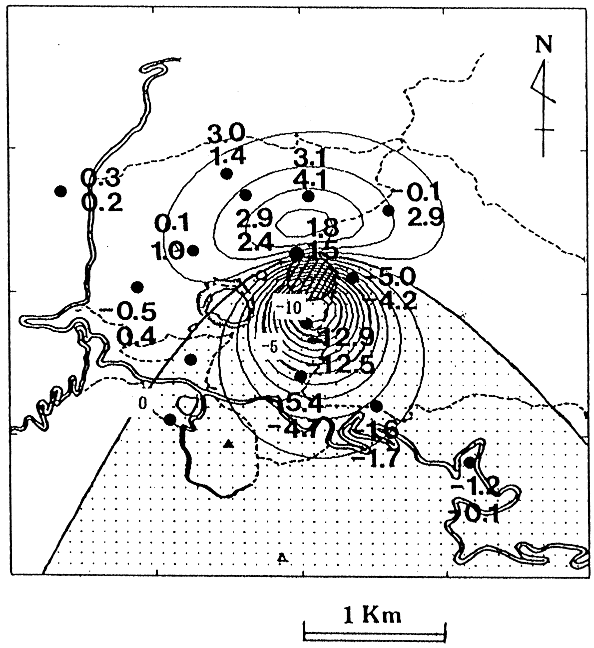


Fig. 7 Dipole model of thermal demagnetization determined by excluding the values at Nos. 13 and 14 observation points (model B). The depth of the dipole is about 550m. Other settings are the same as those in Fig. 6.

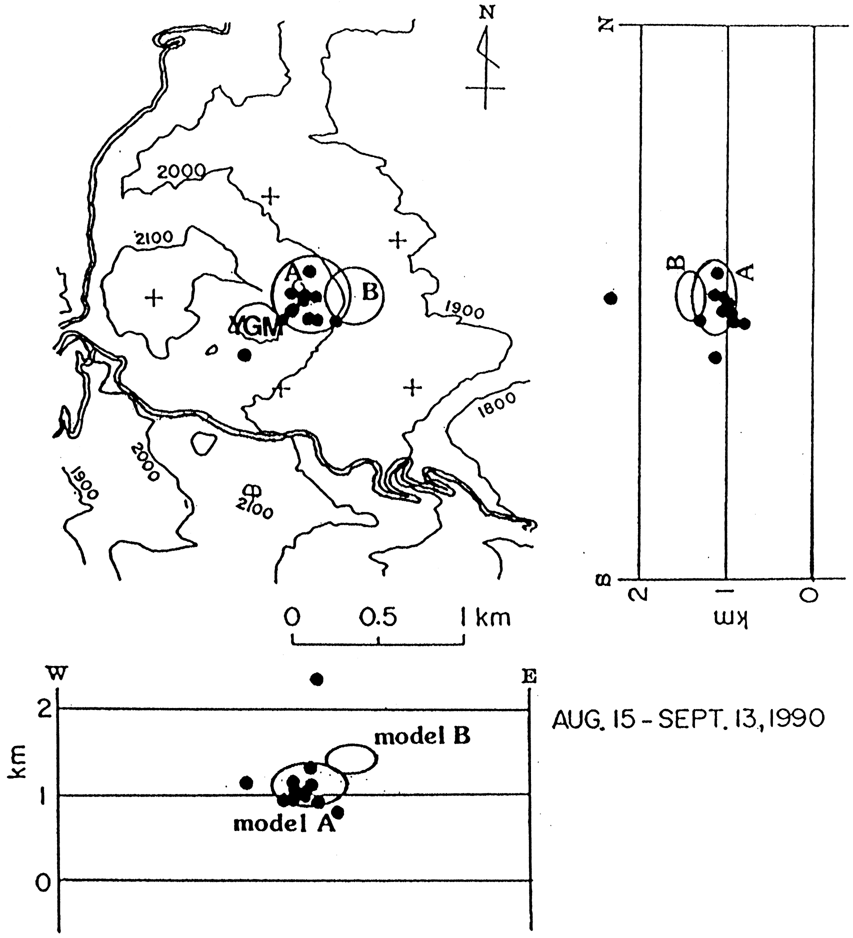


Fig. 8 Distribution of focuses of volcanic earthquakes occurred from Aug. 15, 1990, to Sep. 13, 1990, by Earthquake Research Institute (1990) and estimated thermal demagnetization area. A and B correspond to model A and model B in Figs. 6 and 7, respectively. + marks show the position of the seismograph sensors by ERI.

volcano are considered. One is a direct heating to the surrounding rocks by intrusion of magma, and the other is penetration or circulation of the hydrothermal system. According to the previous reports on electromagnetic research at the Kusatsu-Shirane volcano (Bureau of enterprise of Gunma Prefecture, 1975; Mishina et al., 1985), the resistivity of the entire volcano is low, which is a typical feature of a geothermal region. Especially, an extremely low resistivity zone, which is less than 10 Ω・m, is distributed at the summit area. We suppose that the low resistivity zone suggests the existence of a hydrothermal deposit, and the hydrothermal system played an important role to this demagnetization.

In the case of a progression of the thermal demagnetization by heat up from the hydrothermal deposit, it is supposed that the thermal demagnetized zone sometimes takes the shape of a disk or a thin cone. Generally, a magnetic anomaly caused by a disk-shaped magnetized body is represented by a magnetic dipole when the body exists deeper than a certain depth. In other words, the shape of the demagnetized zone can take various shapes, even though the magnetic changes have been interpreted by a dipole model. Yamazaki and Churei (1991) have estimated parameters of disk or conic shapes which make almost the same magnetic anomaly to the surface as Model B. Typical shapes of the estimated disk or conic model are shown in Fig. 9. It has been pointed out that there is no disk model which makes the same magnetic anomaly as Model B when the depth of its upper surface is shallower than 300 m or deeper than 500 m. In other words, if we suppose that the thermal demagnetization was caused by heating up a disk-shaped hydrothermal deposit, the upper surface depth of the disk must be within the range from 300 m to 500 m. As shown in Fig. 9, various shapes are

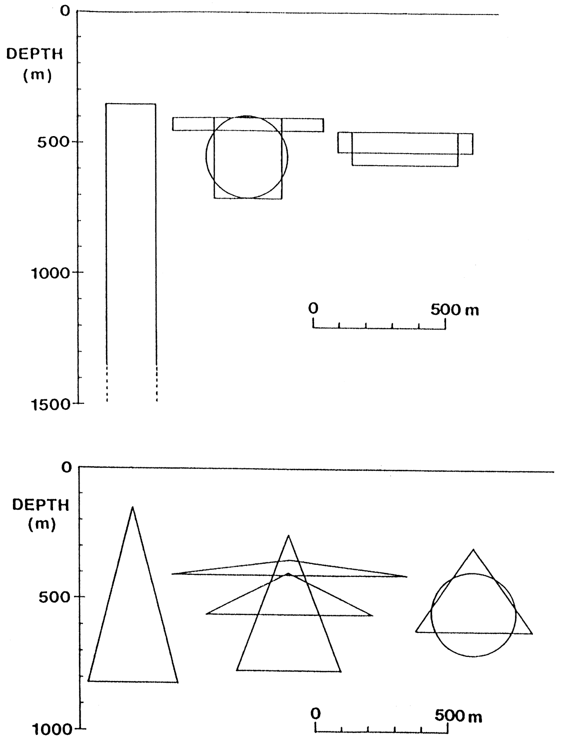


Fig. 9 Examples of columnar and conic demagnetization models which cause nearly the same magnetic anomaly as model B (Yamazaki and Churei, 1991). The spherical model B is also shown for comparison.

possible to take as an equivalent thermal demagnetization model, so that it is difficult to specify a shape from only geomagnetic observation. We need to refer to other geophysical observations to estimate the true shape of the thermal demagnetization zone.

Next we will consider the piezomagnetic effect, which is sometimes usable and sometimes not usable for interpreting the changes in total force. Some piezomagnetic field models, such as an inflation model of a magma chamber, a dike penetration model and so on, have been proposed for volcanomagnetism. Recently, the piezomagnetic field associated with the Mogi model, which is an inflation model of a magma chamber, has been reexamined (Suzuki and Oshiman, 1990; Sasai, 1991). Now we assume that the sphere of model A is a magma chamber and that the increase of internal pressure of the sphere is 1 K bar. Then the estimated total force change by the piezomagnetic effect is shown in Fig. 10. The computation was made by using an analytic formula called TYPE II solution (Sasai, 1991). The parameters used for the computation are listed in

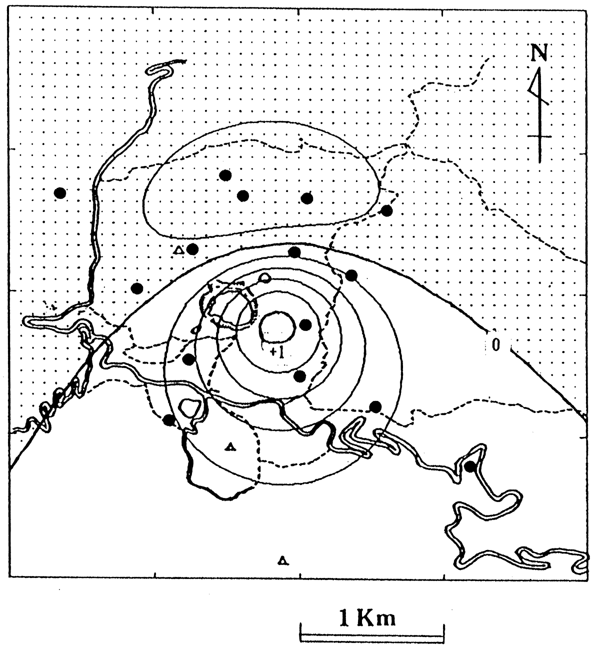


Fig. 10 Piezomagnetic field produced by the presence of an expanded sphere. The size of the sphere is the same as model A. Contour interval is 0.2 nT. Others are the same settings as those in Fig. 6.

Table 2. The computed change pattern of the total force is a decrease at the northern area of Yugama and an increase at the southern area. The pattern is in reverse of that of thermal demagnetization, and the maximum amplitude is 1.0 nT. If the magma chamber is significantly bigger than model A and a considerable decrease in pressure occurs, then we can obtain almost the same total force change as observed by the piezomagnetic effect. However, it is considered generally that a development of volcanic activities under a volcano implies a supply of magma, so that it is hard to suppose that a considerable decrease in pressure occurs in a magma chamber.

Although we cannot conclude because the total force change caused by a piezomagnetic effect can take various change patterns depending on the stress model, it is hard to think that the total force change was caused by a piezomagnetic effect.

6. Experiments on the rock magnetism

We made an experiment on the rock magnetism to know how much the temperature beneath the volcano rises. The samples which were collected near the No. 6 repeat observation point are pyroxene andesite. The samples were rolling stones, but we thought from their colors they were comparatively fresh and unweathering.

A spinner magnetometer was used for the measurement of NRM. At first, an ac demagnetization was performed on the samples until 500 Oe by steps of 50 Oe (4000 A/m). The decreasing tendency of the NRM corresponding to the intensity of the ac demagnetization was decreased rapidly, first by 50 Oe steps, and then gradually decreased by successive steps. Similarly, the directions of NRM showed a large change in the first step, and then it was fixed at the successive steps. The intensities of NRM of the samples are within the range of $1.0 \sim 2.0 \times 10^{-3}$ emu/cc ($1.0 \sim 2.0$ A/m) after operating the first 50 Oe ac demagnetization. We were able to confirm through this measurement that the intensity of 1.0×10^{-3} emu/cc which was used for estimation of thermal demagnetization was a proper value.

Moreover, we measured the characteristics of the thermal demagnetization of the samples under ordinary air conditions. We measured them from normal temperature to 600 °C by steps of 100 °C. We performed a 50 Oe ac demagnetization on the samples before measurement. As shown in Fig. 11, each sample shows almost the same thermal characteristics, and the maximum gradient is recognized at 300 ~ 400 °C.

7. Conclusion

In 1990, many volcanic earthquakes occurred at the Kusatsu-Shirane volcano, which implied an increase of volcanic activities beneath the volcano. Further, geochemical observation by Tokyo Institute of Technology indicated a high level of volcanic activities. At the same time, we observed a remarkable change in total force, which indicated a typical thermal demagnetization pattern. This total force change has been interpreted by occurrence of a large-scale thermal demagnetization beneath the volcano during the interval from 1989 to 1990.

We have proposed two models of thermal

Table 2 Model parameters used in calculation of the piezomagnetic field in Fig. 10.

Depth of the center of the source sphere	D	900 m
Radius of the spherical pressure source	a	230 m
Internal hydrostatic pressure	⊿P	1K bar
Curie point isotherm depth	H	6 km
Stress sensitivity	β	2.0×10^{-4} bar^{-1}
Lame's constant	λ	3.0×10^{5} bar
	μ	3.0×10^{5} bar
Intensity of magnetization	J	1 A/m
Geomagnetic inclination	I_0	49°
Geomagnetic declination	D_0	7° W

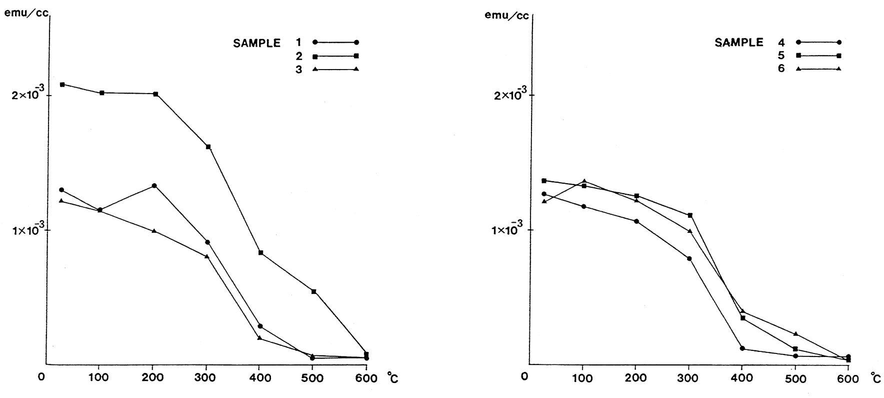


Fig. 11 Thermal demagnetization of the andesite samples

demagnetization, named Model A and Model B, from an analysis of the change of the total force. According to a comparison with the focuses of the volcanic earthquakes, Model A coincided well with those focuses. However, Model B was slightly different. As each model has some strong points, we did not conclude a final model.

Furthermore, it is found by the experiments of rock magnetism on Kusatsu-Shirane andesite that thermal demagnetization will progress effectively when the temperature of the underground rises up to 400℃. However, we do not know to what degree the samples represent the rocks beneath the volcano. As for the intensity of rock magnetization, the remanent magnetization is probably weaker than what was measured, because some places of Kusatsu-Shirane andesite were demagnetized strongly by hydrothermal alteration (Bureau of enterprise of Gunma Prefecture, 1975).

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