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Evaluation of electric and magnetic field monitoring of Miyake-jima volcano (Central Japan): 1995-1999

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Abstract
Results of electromagnetic observations on Miyake-jima volcano for the past five years are summarized. Audio-frequency MT soundings revealed some main features of the resistivity structure: 1) a hydrothermal aquifer in the summit Hatcho-Taira caldera is well identified in its size and position; 2) the older Kuwanoki-Taira caldera is characterized by a relatively low resistive layer (~ a few hundreds $\Omega \cdot$m), surrounded by highly resistive boundaries; 3) the low resistive area of sea water penetration spreads within 1 to 2 km from the coast line including the 1940 and 1962 fissures in NE, but the 1983 fissure zone in the SW is very resistive. The distribution of Self Potential (SP) exhibits two negative (– 200 and – 100 mV) and one positive (+ 700 mV) anomalies. The former correspond to the fissures of 1874 (N) and 1763 (SW) eruptions, while the latter to the fumaroles in Hatcho-Taira caldera. A large-scale hydrothermal system is suggested, in which the meteoric water infiltrated from fissure zones is heated at depth and rises up to the summit fumaroles area. We have conducted joint observations of magnetic field, resistivity and SP since October 1995. Electric and magnetic fields induced by the dominant ocean current Kuroshio flowing around the island is the most serious EM noises of natural origin. The nature of the motionally-induced fields has been clarified through observations with 8 proton magnetometers, 3 short-span SP measurement arrays, and a long-distance SP array over the island connected with telephone cables. The fluctuations in the total intensity prevail along the southwestern coast. Such magnetic field is produced by electric currents in SE-NW, which are generated by the meander of Kuroshio flowing from SW to NE. This relation was clearly demonstrated by the long-distance and short-span SP measurements. Anomalous magnetic variations were observed simultaneously with positive (+ 10 nT) on the north and negative (– 5 nT) on the south around the central-southern area of the island from September 1996 to June 1998. The source of the anomaly, *i.e.* a thermally demagnetized area, was suggested to lie beneath the southern wall of Hatcho-Taira caldera. This is the first observation which indicates heating of the volcano besides the after-effects of the 1983 eruption. Except for the two locally anomalous stations, the geomagnetic total intensity on Miyake-jima island shows a gradual decrease for the past five years. This fact is probably related to the increasing pressure of the magma reservoir at depth as supported by the on-going inflation of the volcano via GPS observations.

Key words *Miyake-jima volcano – electromagnetic monitoring of volcano – volcanomagnetic effect – resistivity – self potential – thermal magnetic effect – electrokinetic phenomena – motionally-induced electric and magnetic fields*

1. Introduction

Miyake-jima island is a basaltic volcano in the Northern Izu-Bonin arc, about 200 km south of Tokyo (fig. 1). Although the radius of the island is only 9 km, the volcano edifice has a size of 25 km, taking account of upheaval from the topographic flat of the sea floor at depth 300-700 m. In this century it erupted very reg-

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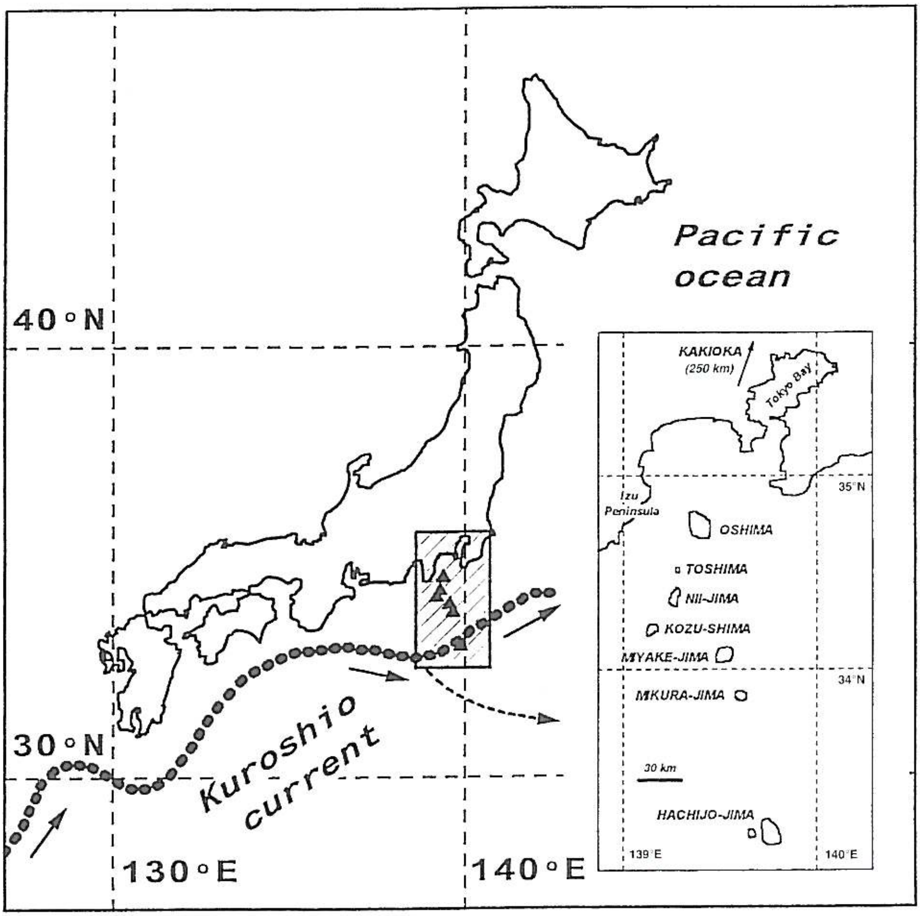


Fig. 1. Map showing the location of the northernmost part of Izu-Bonin arc (the hatched area). The included map shows the locations of Miyake-jima, Hachijo-jima and other volcanic islands. Kakioka Magnetic Observatory (KAK) is located 250 km north of Miyake-jima. Also depicted in the large map is a typical flow-path of the Kuroshio current when flowing smoothly from west to east.

ularly in 1940, 1962 and 1983. At the time of the last three eruptions, some modern geophysical and geological studies were made. However, most of the observations were conducted after the eruptions: the process to the coming eruption has not yet been clarified. During the past decade, geophysical observations as well as geological investigations have been extensively carried out to prepare for a possible activity early in the next century.

We started electromagnetic monitoring of Miyake-jima volcano in October 1995 (Sasai *et al.*, 1997: referred to Paper I). On Miyake-jima volcano, electromagnetic measurements were vigorously made at every three events in this century, which were briefly reviewed in Paper I. Learning from the advances in volcano-electromagnetics since the 1986 eruption of Izu-Oshima volcano (Yukutake, 1990), we aim at combined observations of magnetic field, resistivity and self-electric potential (fig. 2). We have eight proton precession magnetometers (since October 1995), three short-span SP stations (two since October 1995, one since October 1996), long-distance SP measurement array with nine electrodes well distributed over the island connected by telephone cables (since March 1998). We conducted areal survey of SP over the volcano (1995-1997) as well as audio-frequency MT survey of ground resistivity (1997-1998). Recently we installed a controlled source resistivity-meter in the summit caldera (June 1999).

In Paper I we reported remarkable electric and magnetic field disturbances produced by dynamo action of the meander of Kuroshio, a dominant ocean current flowing in the northwestern Pacific. This motionally-induced EM fields are the most serious noises of natural origin against volcano monitoring by electromagnetic method. After the four year observations, the nature of the Kuroshio-induced fields became more or less clear (Sekiguchi, 1998).

In this paper we present the general and global approach we adopt on electromagnetic

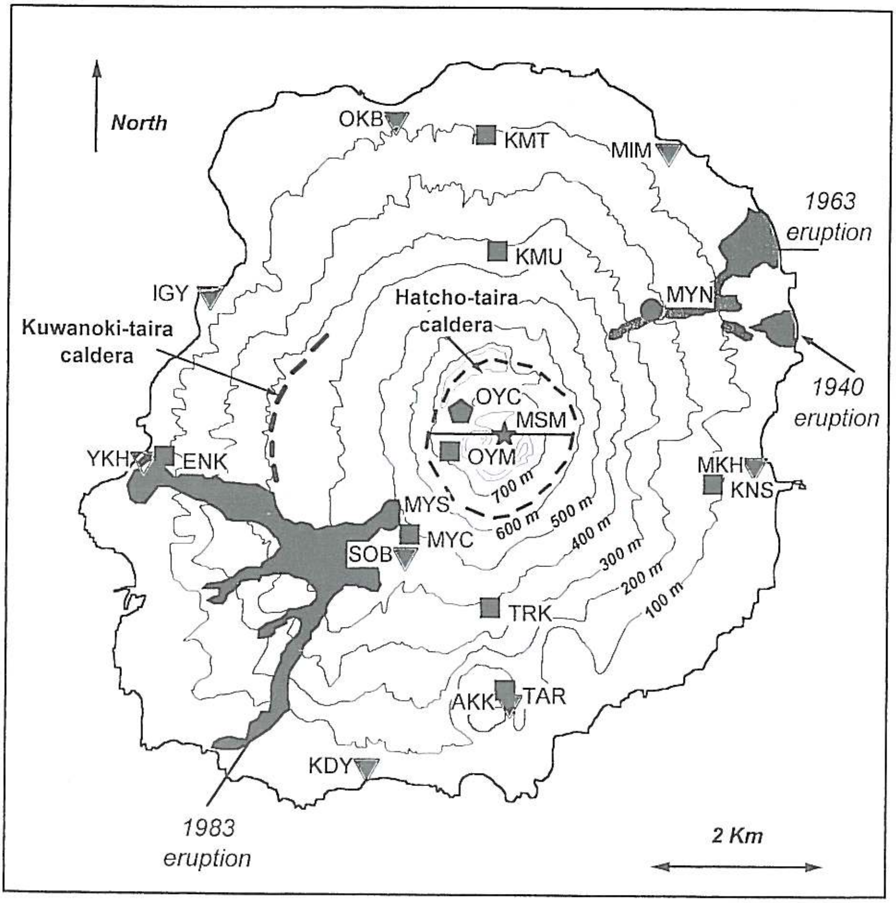


Fig. 2. Location of electric and magnetic field observations on Miyake-jima Island. Solid squares indicate continuously recording proton precession magnetometers, solid circles continuous measurements of self electric potentials with short-span electrodes distances (75 m - 190 m), reverse triangles electrodes for long-distance SP measurements connected with telephone cables, OYC continuous MT station and MSM the controlled source resistivity-meter.

methods to evaluate the structure, dynamism and a future unrest of Miyake-jima volcano. We will deal here with the results of electric and magnetic field observations from October 1995 to December 1999. First we will briefly review some new findings in geology during the past five years. Our resistivity survey and SP mapping can provide us with useful information on the eruption-related structure of the volcano. In order to evaluate the relationship between EM observations and the present-day state of the volcano, we will summarize the results of geophysical observations after the 1983 eruption. Finally, continuous measurements of magnetic field and long- and short-distance self electric potential for the past five years will be presented. We discuss the interpretation of the 1995-1999 data and the prospects of the evolution of the volcanic behavior.

2. Geological background

The main features of the topography of Miyake-jima volcano are shown in the 1:15000 Land Condition Map «Miyake-jima» (Geographical Survey Institute, 1995). There exist two calderas in the central part of the main strato-volcano: *i.e.* the older one «Kuwanoki-Taira Caldera» with 4 km in diameter and the younger one «Hatcho-Taira caldera» of 1.8 by 1.6 km inside the old one. The shape of the eastern half of the older caldera is masked by the central cone Mt. Oyama, on which Hatcho-Taira caldera was formed. However, the analysis of flatness strongly suggests that the old caldera occupies the center of the island. There are several large maars around the entire coast line, which were formed by the phreato-magmatic explosions. Eruptions occurred 14 times since 1085 A.D. (Isshiki, 1964). Recently Tsukui and Suzuki (1998) revised the eruption history of Miyake-jima volcano with the aid of tephrochronology, C14 dating, archeology and historical documents:

1a) Formation of the main composite volcano including the older caldera (Kuwanoki-Taira): until 7000 years BP followed by inactive period up to 4000 years BP.

1b) Formation of the younger caldera (Hatcho-Taira): 400-2500 years BP. The caldera was formed within a few tens of years around 2500 years BP.

1c) Formation of the post-caldera central cone Mt. Oyama: 2500 years BP - 15 century A.D. Summit and flank fissure eruptions.

1d) Mainly flank-fissure eruptions: 1469 A.D. - present. No ash-fall from the summit crater.

Ito *et al.* (1999) investigated variations of the whole rock chemical composition of ejecta during the different epochs from 1a) to 1d). Those during the epoch 1a) are mostly basaltic, while the ejecta in the later periods contain some andesite and dacite constituents. This implies that the ejecta of the main composite volcano came from a large basaltic magma reservoir, while, in the later periods 1b)-1d), subsidiary reservoirs were formed above the main reservoir, from which more differentiated magma extruded.

Amma-Miyasaka and Nakagawa (1998) proposed a unique model for magma-plumbing system of the recent three eruptions by means of detailed petrological analysis of these lavas. In 1940, the summit eruption followed the flank-fissure eruption. However, the chemical composition of these lava flows is classified into three groups, each of which stayed in a different reservoir and extruded through a different vent. The lavas in the 1962 eruption can be classified into two composition groups, which requires two different reservoirs and vents as well; there is no evidence for magma mixing nor differentiation from each other.

Soya *et al.* (1984) had already pointed out that the chemical composition of ejecta in the 1983 eruption consisted of two different groups, which suggests the existence of at least two vents isolated at a deeper depth. However, they did not discuss the possibility of two separated reservoirs. Amma-Miyasaka and Nakagawa (1998) extended the idea of Soya *et al.* (1984) to claim that there existed three, two and two different reservoir-vent systems corresponding to the 1940, 1962 and 1983 events, respectively. This implies that a multiple reservoir system exists beneath Miyake-jima as was the case of the 1986 eruption of Izu-Oshima volcano. For the 1986 event, Aramaki and Fujii (1988) presented a petrological model with three reservoir-conduit systems corresponding to the summit eruption (phase I), the fissure eruption (phase II) and the subsequent intrusive event. These new findings and ideas from geological studies are most important when we consider the possible eruption scenario of the coming activity of Miyake-jima volcano.

3. Resistivity soundings

In 1997 and 1998 several campaigns of magnetotelluric soundings (MT) were performed all over Miyake-jima island (see figs. 3 and 4). More than 80 soundings were done with a higher density on the south volcano flank where deformations are mainly observed (Geographycal Survey Institute, 1998). Cultural noises were encountered on the soundings, especially to the east where no sounding data were available.

The equipment used both natural and man-made electromagnetic signals to obtain continuous electrical soundings from 70 kHz to 0.1 Hz. The system consisted of a receiver and a transmitter. The receiver was composed of two orthogonal horizontal magnetic coils (H_x, H_y) associated with two orthogonal electric lines (E_y, E_x). In the high frequency band, 1 kHz-70 kHz, where the natural electromagnetic field is weak we used an antenna of 400 or 5000 Am^2 to generate an artificial field in orthogonal directions. For each sounding the antenna was placed far enough away from the receiver to ensure a planar wave. In the low frequency band, 0.1 Hz-1 kHz, the natural electromagnetic field was recorded. For each sounding, several data sets were collected, one of which without the antenna to check the quality and the validity of the data.

A preliminary result was summarized by Zlotnicki (1998). Data and detailed results will be presented in Zlotnicki *et al.* (2001). In this paper we focus on some typical features of the resistivity structure (fig. 4).

3.1. *The hydrothermal system in the summit caldera*

The hydrothermal system located on the summit was already observed in the recent past (Utada *et al.*, 1984). The 1997-1998 soundings delineate its outline. The hydrothermal system is confined to the western part of the young Hatcho-Taira caldera and lies over Oyama crater and Oyama mountain (fig. 4). Most probably the hydrothermal system is also developing southward. No trace is observed to the north and east. The roof of the system is located at a few hundreds meters depth (200-300 m). In the central part, the resistive substratum was not reached. This well-confined hydrothermal system (about 1000 × 800 m in size) makes us suppose that thermal transfer below Hatcho-Taira caldera is controlled by sub-vertical conduits. Impermeable geological layers or the geo-morphology of the eastern craters prevent any hydrothermal exchange. The western location of this hydrothermal system, the flat topography of the western wall of Hatcho-Taira caldera and the seismicity observed during the 1962 eruption (Minakami, 1964) could suppose some discharge of ground water flow to the north-east through Hatcho-Taira caldera wall.

3.2. *Seawater penetration*

At low altitude (less than 400 m), the resistivity is controlled by the seawater penetration through the island. Low resistive layers, about 10 $\Omega \cdot$m, are observed up to 2 km away from the coast line. At that distance the upper interface is commonly at 200-300 m below sea level. This general pattern is locally disrupted by existing eruptive axes (*i.e.* 1940, 1962, 1983) and by large maars along the coast (*i.e.* Tairoike maar, Yaema maar). These low altitude craters formed during phreato-magmatic eruptions have deeply entailed the composite volcano up to 1 or 2 km inland, and have favoured the penetration of seawater inside the composite volcano.

The seawater penetration through the main fissure axes seems strongly dependent on the recent past volcanic activity. The area covered by the 1940-1962 fissures located on the north-east coast is of low resistivity. It indicates that seawater has already invaded the eruptive fissures, while the 1983 fissures axis located on the south-west coast remains almost free of seawater infiltration.

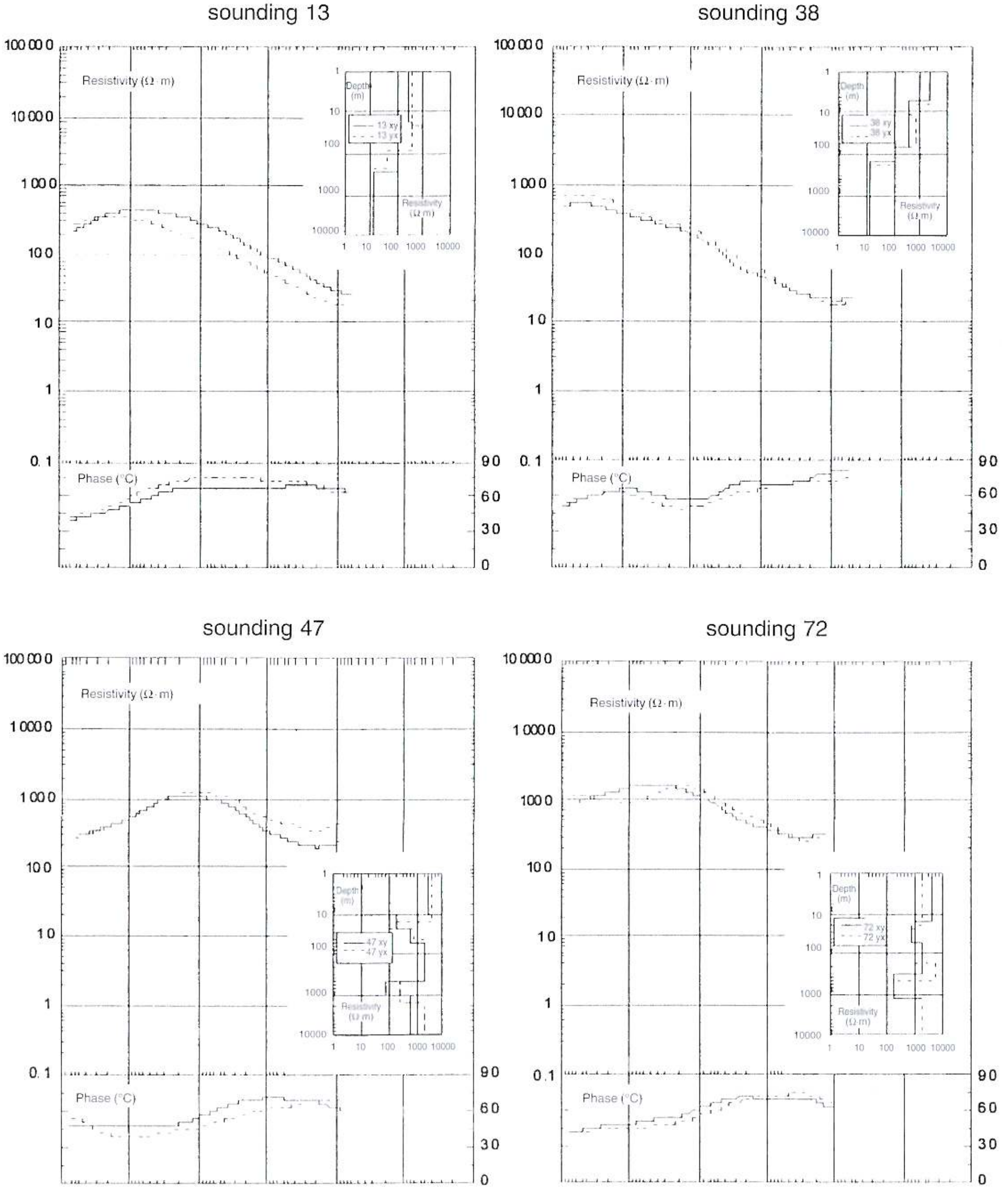


Fig. 3. Examples of MT soundings. See fig. 4 for the location.

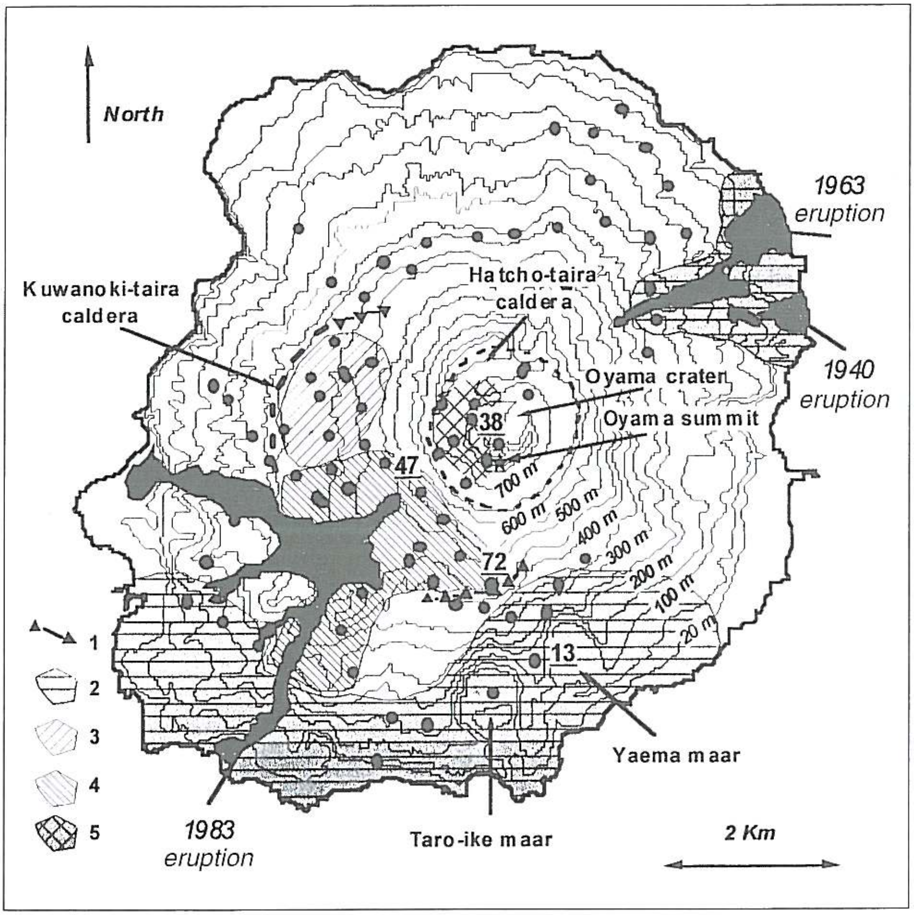


Fig. 4. Some typical features of resistivity structure of Miyake-jima volcano as revealed by MT soundings. 1) Limit and extent of Kuwanoki-Taira caldera; 2) sketch of seawater penetration in the island; 3) intra caldera tuff deposits (more or less swamped by meteoric water); 4) recent and fresh lava flows (hiding partly the SW Kuwanoki-Taira caldera wall); 5) summit hydrothermal system. 13, 38, 47 and 72 are location of soundings presented in fig. 3.

3.3. *The Kuwanoki-Taira caldera*

Many MT soundings were done inside and outside the Kuwanoki-Taira caldera to delineate its contour. The high level cultural noise and the steepness of the topography frequently prevented us making MT soundings. Nevertheless the large number of soundings give new information. The western caldera border drawn in the 1:15 000 Land Condition Map «Miyake-jima» (Geographical Survey Institute, 1995) is confirmed by MT soundings. This border seems to prevent the seawater penetrating more deeply inside the Kuwanoki-Taira caldera. Between this western wall and the Western Hatcho-Taira caldera wall, a more or less homogeneous superficial medium, 200-800 $\Omega \cdot$ m in resistivity, is recognised. This flat altitude area corresponds to the refilling of deposits emitted by the 2500 years BP to historical volcanic activity, and swamped by meteoric water. If we take into account the limits between low and medium resistivity zones, the western border of Kuwanoki-Taira caldera could run to the north-east as presented in fig. 4.

To the south a high north-east-south-west resistive zone is well observed. It can be associated with the major south-west fissural axis. This result shows that the Kuwanoki-Taira caldera wall has been destroyed and overflown by eruptions. It corresponds to the main weakness zone of the volcanic edifice. This high resistive zone extends to the south-east but suddenly disappears to the north of Tairoke maar. Two hypotheses can be envisioned. This high resistive zone extending to the east can be considered as a fissural axis of south direction. In such hypothesis this axis could be associated with the dynamism at the origin of Tairoke maar. On the other hand, the sharp limit between the resistive medium and the low one corresponding to the extent of the seawater in the island defines the south border of Kuwanoki-Taira caldera wall. If we accept this assumption the contour of the caldera could be the one presented in fig. 4.

4. Self-potential mapping

After the SP surveys in 1991, 1995 and 1996 (Paper I), we conducted a supplemental one in 1997 to confirm a detailed picture of the SP fields over a major part of Miyake-jima island. All the data are compiled as shown in fig. 5a with a contour interval of 100 mV. The values are represented as the relative ones to the tentative reference point (double circle in fig. 5a). The terrain effect is easily seen below altitudes of about 450 m: SP decreases as the ground surface elevation increases. A linear least-squares regression analysis of the terrain effect yields a relation as $SP = 108.7-1.07\,H$, where SP is the electric potential value in mV and H is the sampling point elevation in meters above sea level (Paper I).

The SP anomalies corrected for a mean terrain effect are shown in fig. 5b for traverse line A-B. The main positive anomaly more than 700 mV over the summit area is the important feature of the present study. The negative anomaly on the north mountainside (about − 250 mV) corresponds well with the distribution of many craters connected with the fissures formed in 1874, while that on the south mountainside (− 100 mV) is correlated with the fissures formed in 1763 and older ages (Isshiki, 1960; Nakamura, 1984).

It is well known that the electrokinetic potential may play an important role in generating the SP anomalies amounting to more than several hundred mV (*e.g.*, Zlotnicki *et al.*, 1994). Ishido (1981) presented a theoretical model that electrokinetic potentials caused by upward movement of heated ground water are the principal cause of the large positive anomaly in the geothermal regions while those associated with descending meteoric water are responsible for the negative anomaly. Taking account of his model, we would conclude that a substantial amount of the precipitation (more than 3000 mm/yr) over Miyake-jima island probably recharges highly permeable fissures and craters in 1874 and 1763 to generate the observed negative SP anomalies. Hot volcanic gas from relatively deep-seated magma heats up the recharged water to drive the intensive upward flow and thereby the large positive SP anomaly is generated on the summit area.

5. Magnetic field and long-distance self potential measurements

Now we are to present time variations of electric and magnetic fields for the year 1995-1999 on Miyake-jima volcano. We installed eight continuously recording proton magnetometers in 1995. Within six months, it turned out that the motionally-induced magnetic fields due to Kuroshio ocean current amount to a few to 10 nT (Paper I). We noticed that short-span electric field variations at MYN and MYS (see fig. 2) show similar changes to the magnetic field. This suggests that electric field data can be used to compensate for magnetic field disturbances due to Kuroshio. However, in the rainy season the electric field suffered a large amount of drift; the parallelism between electric and magnetic field variations broke (Paper I).

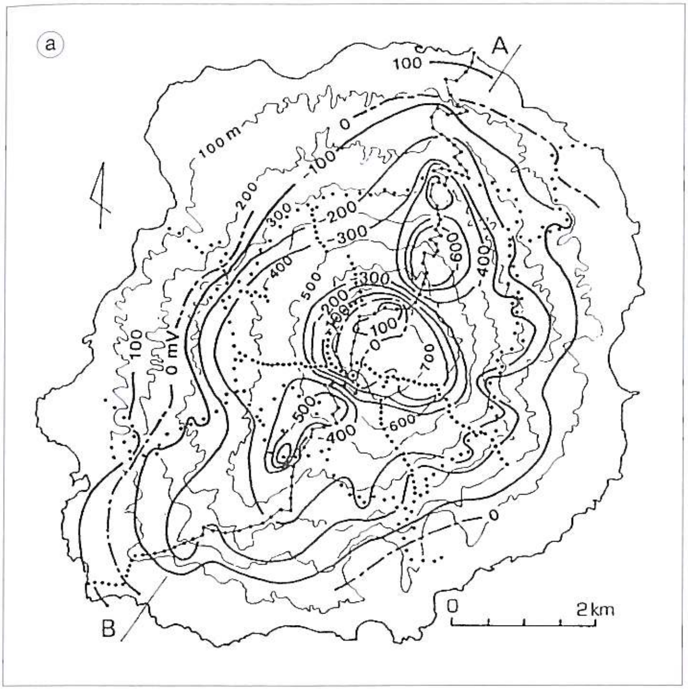
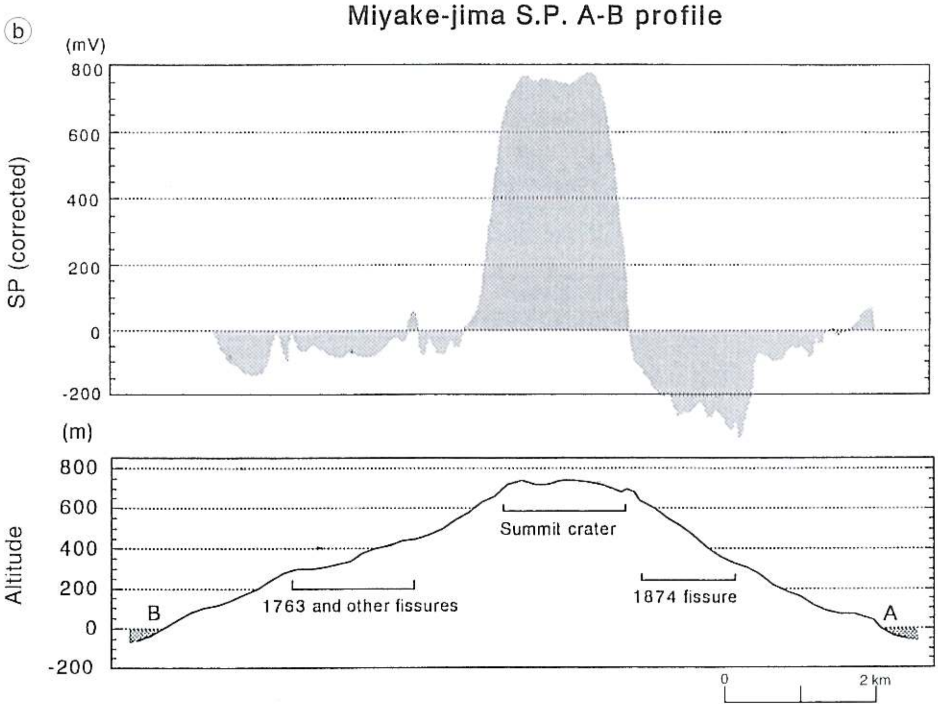


Fig. 5a,b. a) Topographic map of Miyake-jima volcano (contour interval: 100 m), survey stations (solid circles) and contour map of the SP distribution (contour interval: 100 mV). The double circle denotes the reference station. b) SP anomalies corrected for the mean terrain effect (– 1.07 mV/m). SP values at observation points linked with thin line are projected onto the traverse line A-B in (a). Topographic profile is also shown.



Instead, we buried electrodes at eight coastal and one inland sites, connected them with telephone cables and began long-distance SP measurements in March 1998. A data logger was installed at AKK in fig. 2. The potential differences between each electrode and AKK are sampled every 10 s and telemetered to ERI. This observation system was developed as what is called network MT method for deep resistivity sounding (Uyeshima *et al.*, 2001).

Figure 6 shows electric field variations for five channels during the period from March 1998 to December 1999. The upper two curves show the potential differences between two parallel base lines in the SE-NW direction, *i.e.* AKK-YKH and MKH-OKB. The middle two curves show those between two parallel base lines in the NE-SW direction, *i.e.* OKB-YKH and MKH-AKK. The bottom curve shows the potential difference changes at the center of the island (SOB) relative to the coast (AKK). We notice the following:

1) The electric field variations along two parallel lines are very similar with each other. However, the top and bottom two curves show some long-term trends, which is ascribed to the drift at AKK. The cause of the drift is not clear.

2) Disturbances in the self potential difference are the most dominant in the SE-NW direction, while they are minimal in the perpendicular direction.

3) The bottom curve (SOB-AKK) indicates that long-term self-potential difference between the inland and coastal point is small for the period concerned.

Figure 7a shows changes in the total intensity at five stations along the central N-S line of the island, while in fig. 7b those at three stations along E-W line on Miyake-jima and at MKR (Mikura-jima island, about 20 km south of Miyake-jima) and HJJ (Hachijo-jima island, about 70 km south of Miyake-jima: Hachijo Hydrographic Observatory, Hydrographic Office, Japan Maritime Safety Agency), during the same period as fig. 6. These curves show daily mean of simple differences between each station and KAK (about 250 km north of Miyake-jima, Kakioka Magnetic Observatory, Japan Meteorological Agency).

Both in fig. 6 and figs. 7a,b, the tide-induced electric and magnetic fields of diurnal and semi-diurnal periods vanish by daily mean averaging. On Miyake-jima island, irregular variations with a week to a few months' duration prevail at stations near the southern (TAR) and western (ENK) coasts. As demonstrated in Paper I, these fluctuations occur during the meander of Kuroshio current around Miyake-jima island.

Sekiguchi (1998) made a detailed analysis of tide-induced magnetic fields on Miyake and successfully explained the relationship between the total intensity variation and the direction of ocean current flow. By analogy with the tidal magnetic variations, he supposed the reason why Kuroshio-induced total intensity variations are much larger on the southwestern coast on Miyake-jima island. The meandering Kuroshio flows from SW to NE around the island, which induces electric current in SE-NW direction; the electric current is deflected away from the resistive island, which produces a downward vertical magnetic field on the southwestern side and an upward one on the northeastern side of the island; hence the total intensity variation is intensified on the SW but reduced on the NE side of the island.

Figure 6 exhibits a remarkable contrast in amplitudes of electric field variations between the SE-NW and its perpendicular direction. Most of the Kuroshio-induced electric currents flow in the SE-NW direction, which verifies Sekiguchi's (1998) interpretation. Comparing fig. 6 and figs. 7a,b, we find that the total intensity variations at TAR and ENK closely resemble the electric field variation in the SE-NW direction. We may be able to eliminate the Kuroshio-induced magnetic field using long-distance electric field data as reference input.

Figures 8a,b show the total intensity changes during the period from October 1995 to December 1999 for the same stations as in figs. 7a,b. Five day means of simple differences between each station and KAK are plotted:

1) At OYM station close to the summit crater, the total intensity continued to increase. The increasing rate was high for the period from the middle of 1996 to the middle of 1998.

2) For the same period (1996-1998), the total intensity decreased at TRK on the southern flank. The variations at OYM and TRK look like a paired anomaly.

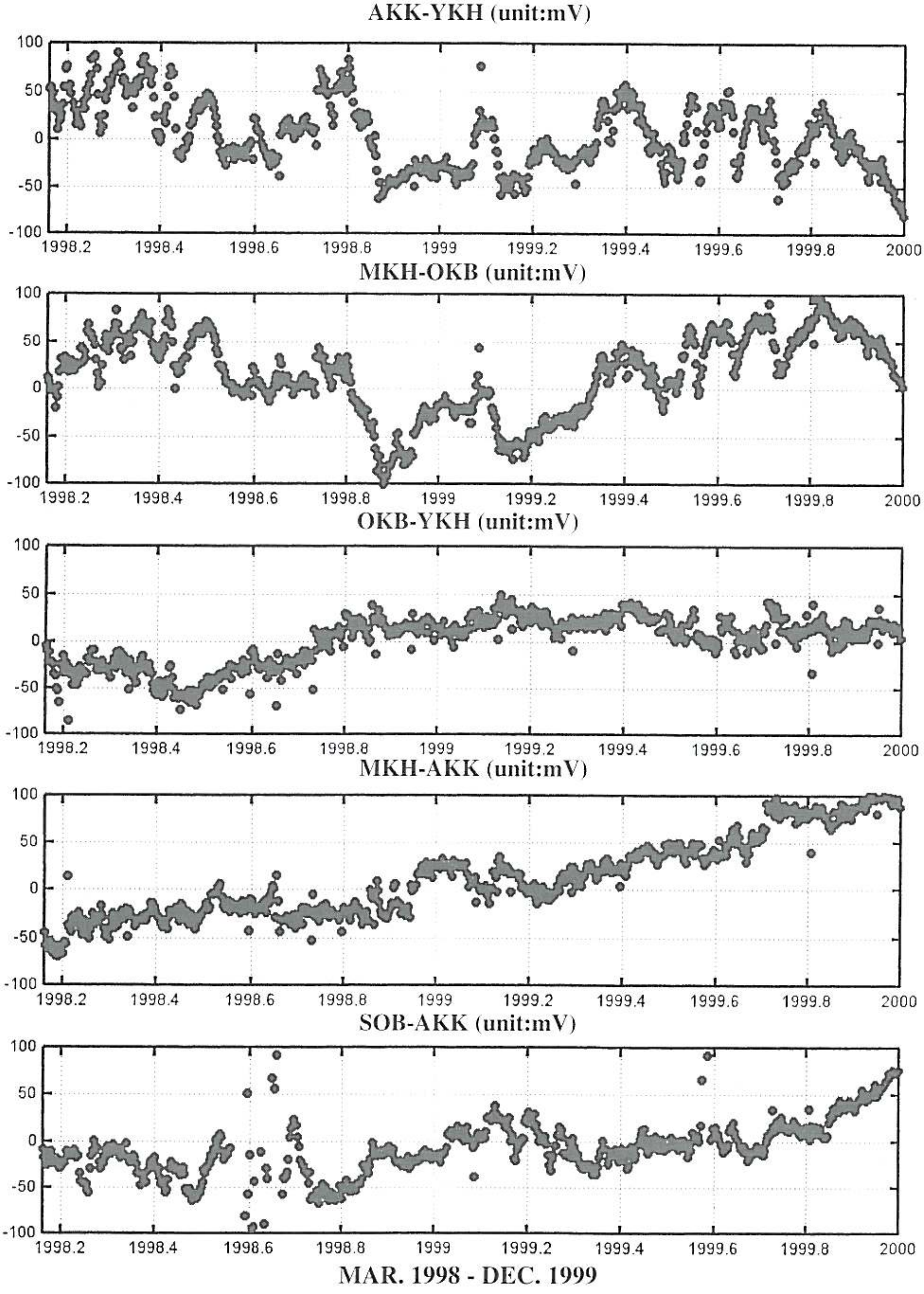


Fig. 6. Daily means of long base line self potential differences. The upper two curves indicate the potential differences in the SE-NW direction, while the middle two those in the perpendicular NE-SW direction (see fig. 2). The bottom curve shows the potential difference between the inland and near shore station. The irregular variations (June-August, 1998) in the bottom curve are due to disconnection of wire at SOB.

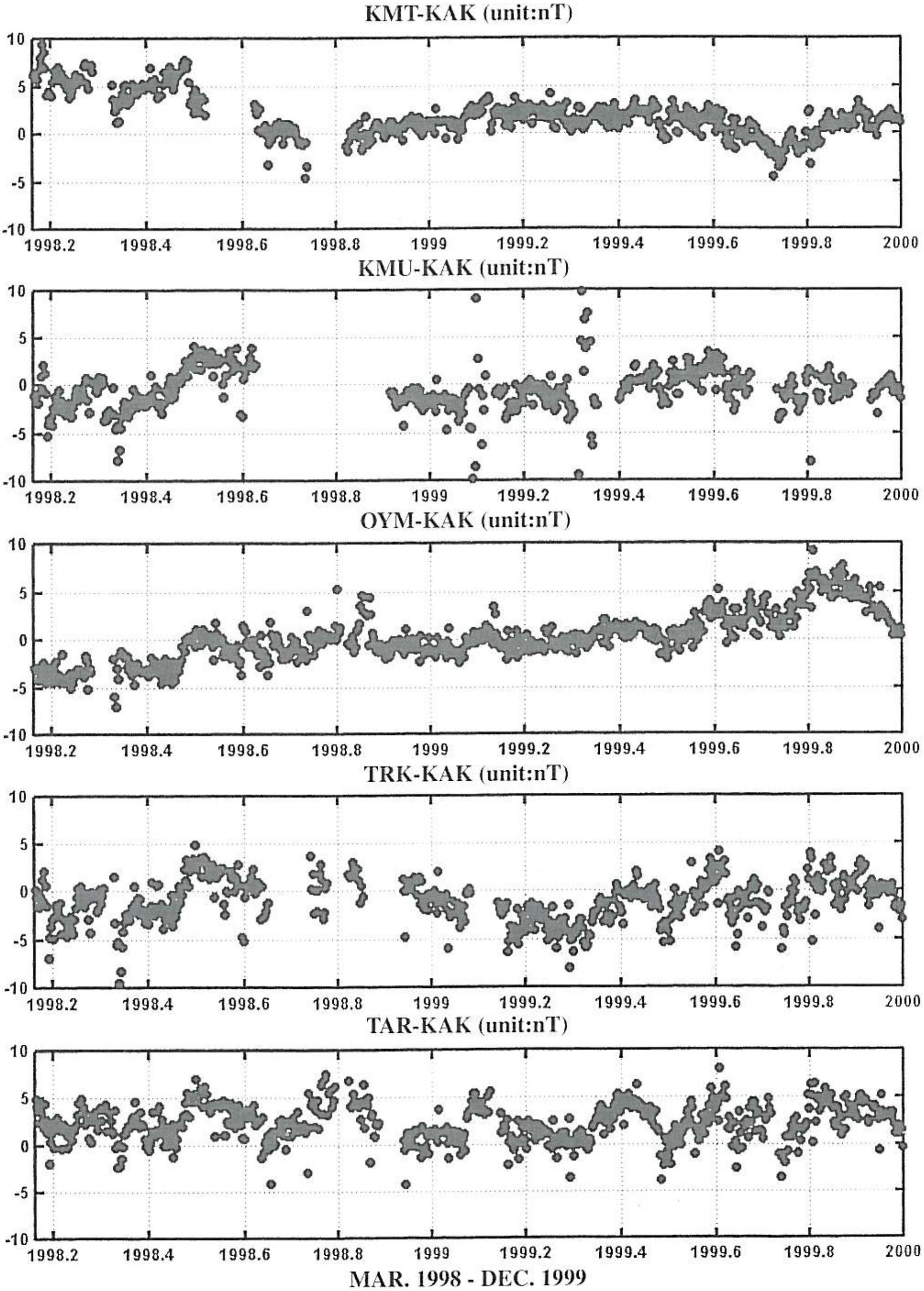


Fig. 7a. Changes in the total force intensity at stations along the central N-S line on Miyake-jima island relative to KAK. Daily means of simple differences are plotted. Unit in nT.

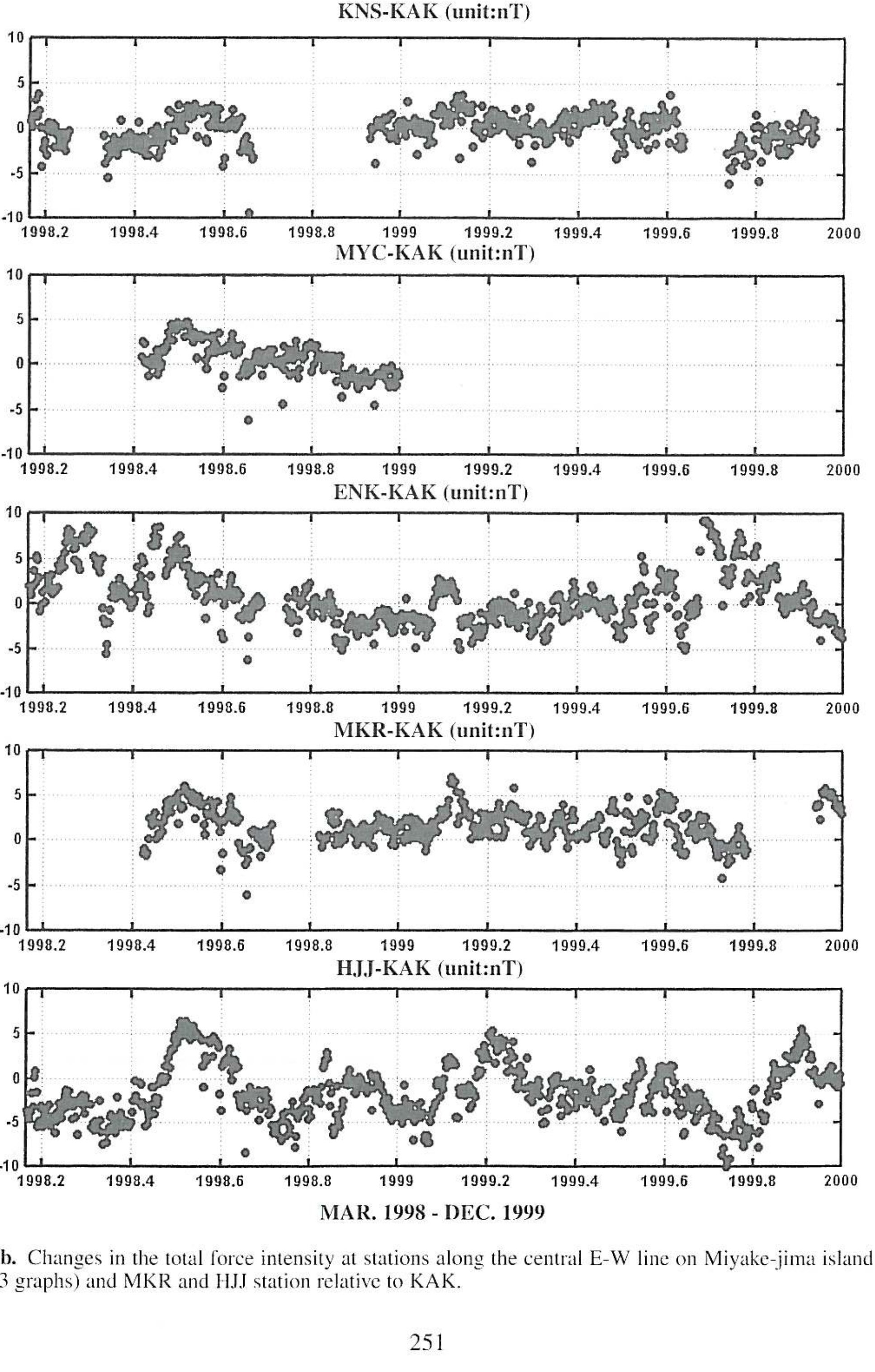


Fig. 7b. Changes in the total force intensity at stations along the central E-W line on Miyake-jima island (the upper 3 graphs) and MKR and HJJ station relative to KAK.

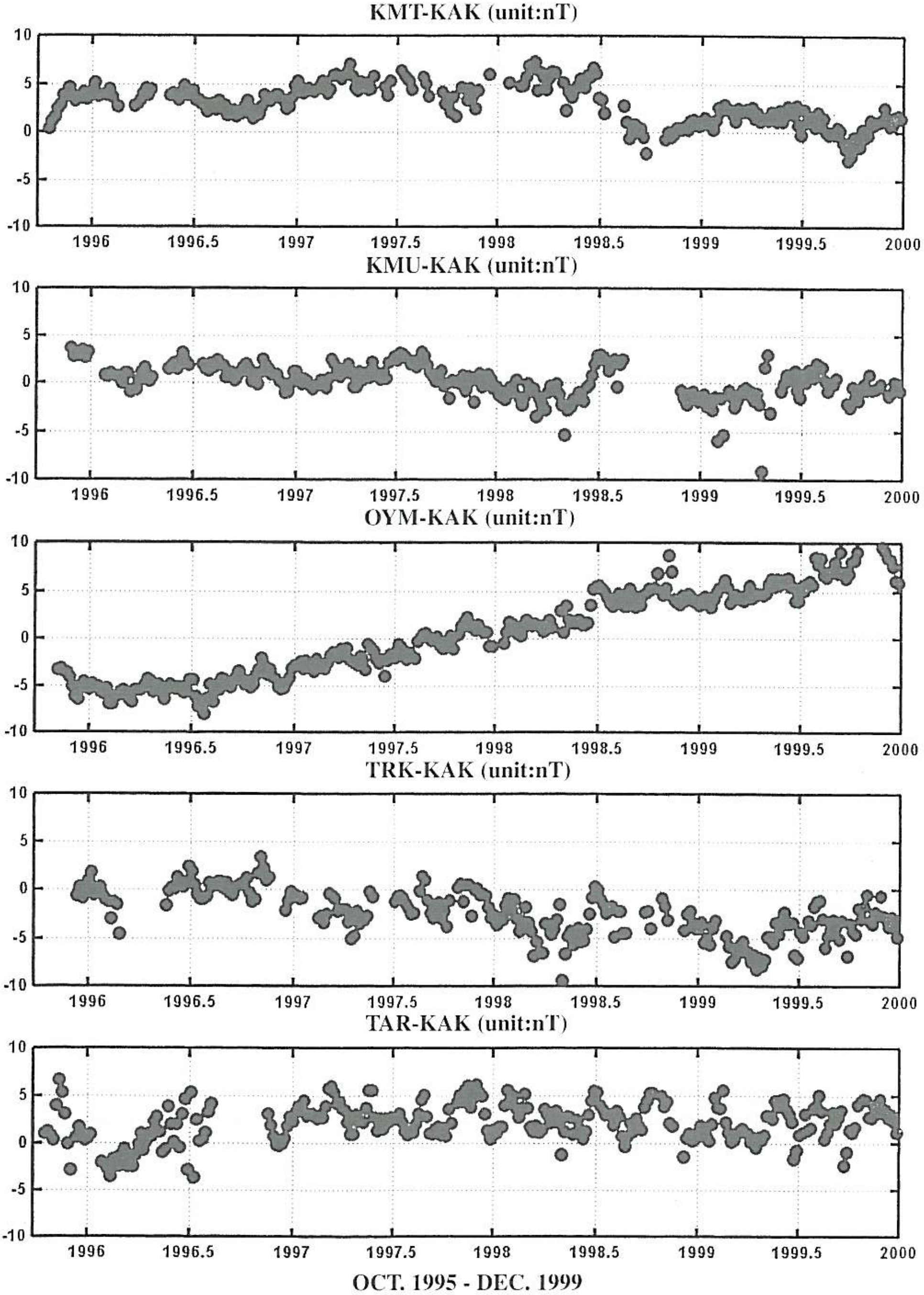


Fig. 8a. Changes in the total force intensity at stations along the central N-S line on Miyake-jima island. 5-day means of simple differences relative to KAK are plotted.

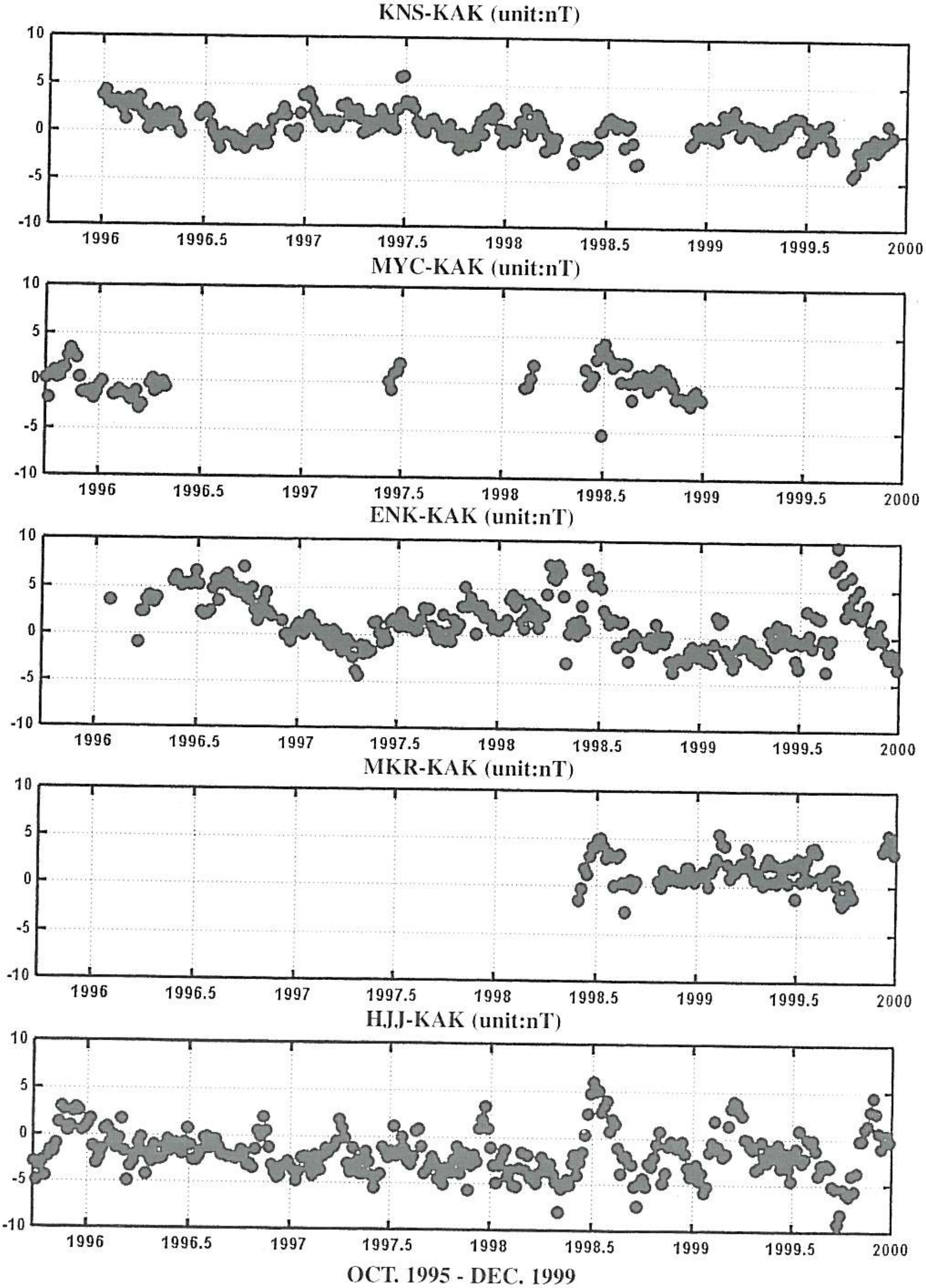


Fig. 8b. Changes in the total force intensity at stations along the central E-W line on Miyake-jima island (upper 3 graphs) and at MKR and HJJ station relative to KAK.

3) On the north (KMT, KMU), east (KNS) and west (ENK) sides of the island, the total intensity slightly decreased, while on the south (TAR) it remained unchanged despite major disturbances due to Kuroshio current.

4) At HJJ, the total intensity remained constant relative to KAK for the past four years.

We will discuss the causes of these magnetic changes in the last section.

6. Volcano monitoring by continuous electric measurements

In order to monitor a possible (i) disturbance of the superficial and summit hydrothermal system in Hatcho-Taira caldera and (ii) changes in the ground water pattern within volcano, in particular along some of the major eruptive axes (those of 1940, 62, 83), we progressively set two self-potential stations on the volcano flanks (see Paper I) and one continuous data logger of the resistivity on the volcano summit.

6.1. *Short-distance self-potential measurements*

By the end of 1995, two self-potential stations, MYN and MYS, were set along the north-east and south-west eruptive axes, respectively (fig. 2). The potential difference of orthogonal lines, the lengths of which are between 60 m and 200 m, is locally recorded on a 4 Mb flash card with a 60 s sampling. Pb-PbCl$_2$ electrodes are buried at several tens of centimetres deep.

Figure 9 shows the mean daily values at MYN station in two orthogonal directions. As far as the period 1996-1998 on the east-west component is concerned, we can assume that there was no noticeable drift on these electrodes. If we extend this assumption on the total time-span and on all the lines we can outline several results. We observe a large annual variation on the NS line (in fact N345°E), which is sharply disturbed by negative spikes due to typhoons occurring every year after summer. The EW line is less affected by such phenomena.

The reliability of short-distance variations on both lines is confirmed by comparison with long-distance self-potential measurements (fig. 6). The pattern of the variations is very similar to those observed in (MKH-OKB) difference; this line crosses the northern part of the island in a NW-SE direction. Therefore short-distance self-potential measurements seem efficient enough to monitor the electric field over several years, even if rainfalls or typhoons disturb the records during several weeks. A weather station is used to discriminate climatic changes from electric variations due to Kuroshio ocean current and the possible volcanic activity.

6.2. *Monitoring of the hydrothermal system by continuous resistivity soundings*

The hydrothermal system located within Hatcho-Taira caldera became very active during the last eruptions; *i.e.* one year after the 1962 and one month after the 1983 erptions (Kagiyama *et al.*, 1984). But no detailed work was devoted to resistivity changes during the pre-eruption stage. We tentatively installed in 1999 a continuous monitoring system of the resistivity through the caldera in the east-west direction, *i.e.* MSM in fig. 2, lines of 600, 1000 and 1400 m-long were used to inject current inside the caldera. Two lines, of 100 and 150 m-long, buried in the same direction, were used as receivers. A current of 300-400 mA was injected every six hours in the three lines of injection, and the potential was measured on both receivers. The mean resistivity, for 600, 1000 and 1400 m lines, was 260, 70, 175 $\Omega \cdot$m, respectively. These values are well in accordance with those obtained by MT soundings in the west part of the caldera. During one month's data recording, the resistivity remained stable within 1 $\Omega \cdot$m except on the shortest line which is probably more affected by the superficial activity of the hydrothermal system of Oyama and the climatic changes (rainfalls and seasonal temperature changes).

7. Other geophysical observations

In the 1990's, various kinds of geophysical observations were intensified in Miyake-jima volcano, such as seismic array, repeat leveling

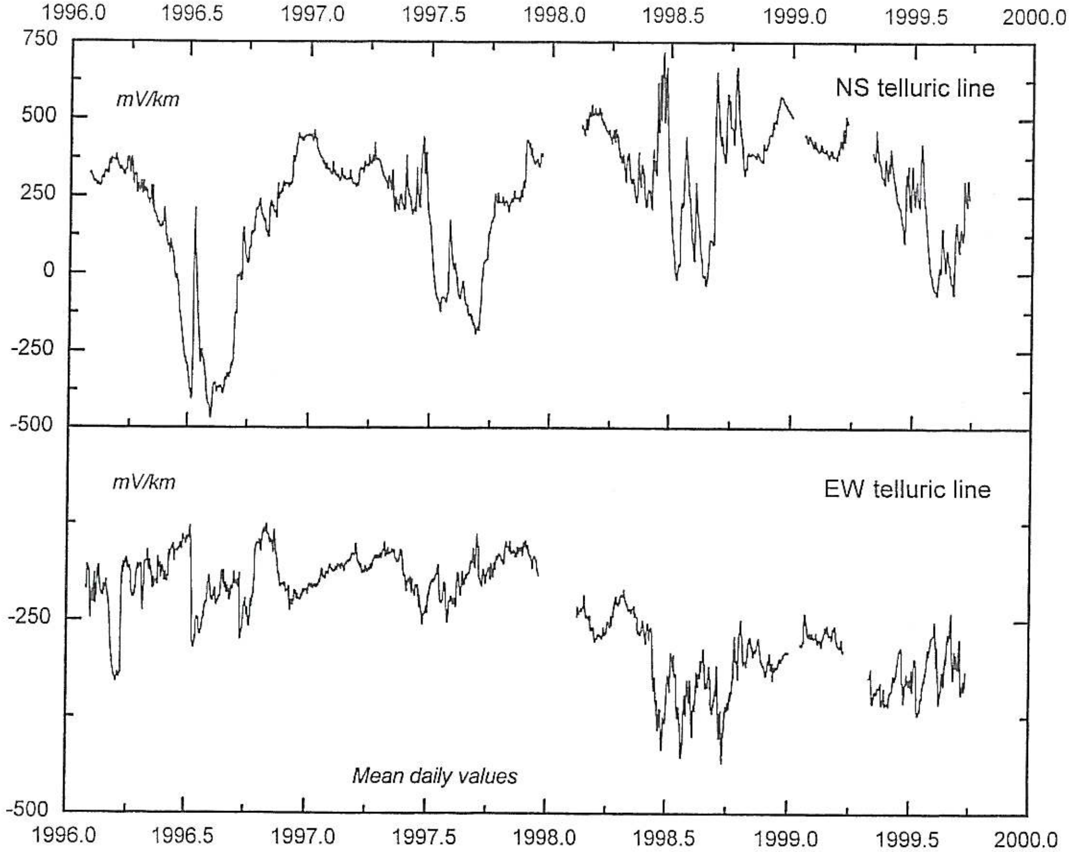


Fig. 9. Daily mean variations of self potentials at MYN.

survey, precise gravity, GPS, bore-hole strain measurements and so on. After a few months of seismic activity which followed the 1983 eruption (Ueki *et al.*, 1984), the seismicity in and around Miyake-jima island was quiescent. The only exception was swarm earthquakes near around rhyolitic volcano islands, Nii-jima and Kozu-shima, about 30 km west, and a swarm activity about 30 km south from Miyake in November, 1990. NIED (National Research Institute for Earth Science and Disaster Prevention) established 5 bore-hole seismo-strainmeters. Low frequency earthquakes (dominant frequency 1-2 Hz) of *M* 2.5 occurred on April 25, 1999, located around the center of the island at a depth of 26 km (NIED, 1999). The causal relationship between these earthquakes and the coming eruption of Miyake-jima volcano is not clear.

We will review some important results of geodetic observations. A leveling survey was repeated along a round road along the coast line on Miyake-jima island. Since the leveling route occupies only a portion of the volcano edifice, the overall height change looks as if the island is inclined on and off in the NE-SW direction (Yokoyama and Maekawa, 1984). However, such apparent inclination can result from a large-scale inflation-deflation due to some pressure sources. Tada and Nakamura (1988) reanalysed the repeat leveling data during the period from February 1979 to January 1986, including the

1983 eruption. They applied these data to a simple pressure source model (Mogi, 1958):

i) In the pre-eruption stage (February 1979-December 1982): maximum uplift 5.5 cm.

ii) Co-eruptive stage (October 1983): maximum depression 20 cm or more.

iii) In the post-eruption stage (November 1983-January 1986): maximum uplift 18 cm.

iv) The center of dilatation for the stages (i) and (iii) was estimated at around 1-2 km SW from the summit crater and at a depth of 8 km.

GSI (Geographical Survey Institute) and Tokyo Metropolitan City Office extended the leveling route by adding an encircling road halfway up the summit to the route along the coast, both of which are connected by a road reaching the summit caldera. According to GSI (1998), the vertical ground movement from 1988 to 1997 can be regarded as the sum of inclination toward NNE (relatively 5 cm) and some local movement around the fissures formed by the 1983 eruption. The former was interpreted as due to inflation of the magma reservoir proposed by Tada and Nakamura (1988). The latter was ascribed to an after-effect of the 1983 eruption or to formation of some new tensile cracks.

GPS observations have been conducted by GSI and the university group since 1994. Figure 10 shows the horizontal movement over the island for a year from 1996 to 1997 (Nagoya Univ. *et al.*, 1998). Arrows indicate displacements relative to a tentative fixed point on the NNE side of the island. The position of the center of dilatation estimated by Tada and Nakamura (1988) is also shown with a circle. Expansion of the island centered at somewhere around the circle is a dominant feature of the horizontal displacements.

The same figure depicts an array of continuous GPS measurements by GSI, *i.e.* base-lines G1-G2 and G3-G4. In particular, the base-line G1-G2 was established in July 1994. During the period from July 1994 to October 1998 (GSI, 1999), the horizontal distance between G1 and G2 continued to extend at an almost constant rate of 2 cm/yr. Also G2 shows gradual uplift relative to G1 at a rate of 1 cm/yr. This implies that G1-G2 baseline runs across around the inflation center and that G2 is closer to the center (GSI, 1999). The horizontal distance between G1 and G2 increased at an almost constant rate for the past five years. However, the rate of expansion seems slightly declined after 1997. We will discuss this later in the final section.

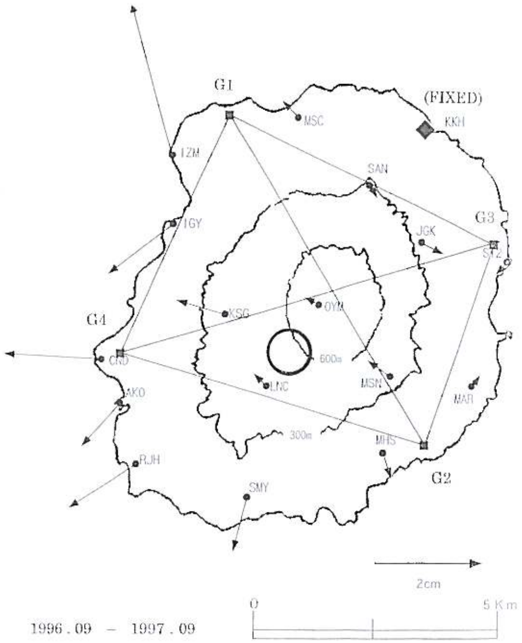


Fig. 10. Horizontal crustal deformation (arrows) observed by GPS repeat surveys on Miyake-jima island during the period from September 1996 to September 1997 (after Nagoya University *et al.*, 1998). KKH on the NE coast is the fixed point. The stations G1 to G4 are continuous GPS measurement sites by GSI (GSI, 1998, 1999). A large hollow circle is the position of the center of dilatation before and after the 1983 eruption as estimated from leveling data by Tada and Nakamura (1988).

8. Discussion and conclusions

The most outstanding changes in the geomagnetic total force intensity for the five year period are the increase at OYM by 10 nT and the decrease at TRK by – 5 nT during the period from September 1996 to June 1998. These variations took place simultaneously, which suggests a common source. The increase in the total intensity at OYM might be easily attributed to the cooling of a hydrothermal aquifer in the Hatcho-Taira (summit) caldera. The size and position of this low resistive aquifer are well identified by MT soundings (Section 3). In fact, the resistivity of this aquifer continued to decrease after the 1983 eruption until May 1985 and remained almost constant (Utada *et al.*, 1986). Correspondingly, a repeat survey point close to OYM station showed a decrease in the total intensity (– 25 nT) until December 1985 and turned to increase by 5 nT until December 1992 (Yamamoto *et al.*, 1993). OYM station is located above the southern periphery of the hydrothermal aquifer: its cooling effectively increases the magnetic total field at OYM.

However, such a magnetized body can produce positive magnetic field at most by 1 nT at TRK, which is quite opposite to the observation (– 5 nT). Moreover, we have to explain how the remagnetization, or the cooling, of the hydrothermal aquifer accelerated since September 1996 (5.7 nT/yr) in contrast to the gradual recovery rate of 0.7 nT/yr (1985-1992). A rapid increase in the temperature within a volcano can be easily ascribed to injection of hot materials; but a rapid cooling mechanism is rather difficult to imagine in this case. An alternative source for the total intensity changes at OYM and TRK is the thermal demagnetization at a shallow depth between OYM and TRK, somewhere closer to OYM. The source position is not unique: the southern rim of the Hatcho-Taira caldera is one of its candidates, because the fractured caldera wall could be a path for hydrothermal fluids.

Figure 11 presents a schematic cross section of demagnetized and remagnetized areas within Miyake-jima volcano since the 1983 eruption (Sasai *et al.*, 1984; Yamamoto *et al.*, 1993; Paper I):

1) A is the demagnetized area during the period from October 1980 to October 1983. Magma was supposed to have stayed there for a short period of time and to have extruded to fissures B in the southwestern flank.

2) At the hydrothermal aquifer C beneath the fumarols in the summit caldera, demagnetization went on from October 1983 to December 1985. It was gradually magnetized again until December 1992 (Yamamoto *et al.*, 1993).

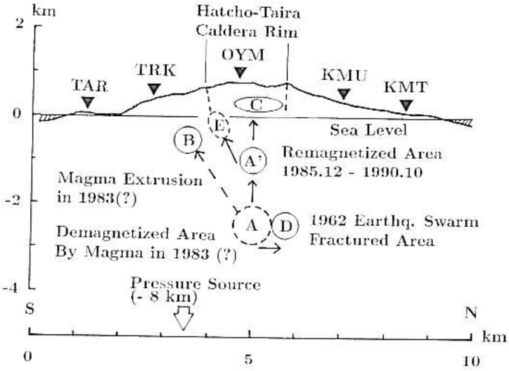


Fig. 11. A schematic representation of the sources of magnetic changes since the 1983 eruption. The topography along the central N-S line of Miyake-jima island is shown. The pressure source for the past 5 years is supposed to lie around the southern flank of the volcano at a depth of 8 km below sea level. Arrows indicate the flow of hydrothermal materials while the dashed arrow shows a possible path of magma.

3) D was rapidly demagnetized from October 1983 to April 1984, which coincides with the source region of swarm earthquakes just after the 1962 eruption. Hydrothermal fluid should have penetrated into the fractured area D after the 1983 eruption (Nakagawa *et al.*, 1984).

4) Yamamoto *et al.* (1993) found that the area A' (1 km below the sea level) connecting A and C was remagnetized from December 1985 to October 1992. The area A' should have been demagnetized prior to the 1983 eruption.

5) The most likely source for the 1996-1998 magnetic changes at OYM and TRK is suggested to be around the area E, which lies beneath the rim of the summit caldera. Unfortunately, MYC has long been in defect and we can poorly constrain the source position E.

In figs. 8a,b, we note that the total intensity decreased by – 1 nT/yr relative to KAK at stations on Miyake-jima island except for OYM and TRK. According to fig. 8b, the difference between HJJ and KAK was roughly constant from 1995 to 1999. We may assume that the secular variation rate of the total force intensity around the Southern Izu Islands region including Hachijo-jima and Miyake-jima islands is almost the same as the one at KAK. Hence, we can conclude that the overall total intensity on Miyake-jima island slightly decreased during the past five years.

This fact is important, because a similar phenomenon was observed before the 1986 eruption of Izu-Oshima volcano. Yukutake *et al.* (1990) reported that the total intensity had been decreasing for the period from 1977 to 1981. During the same period, Izu-Oshima volcano was inflating (Watanabe, 1998). Then the inflation of the volcano stopped, and simultaneously the total intensity at a few stations over the island recovered to the ordinary secular change rate after 1981 until 1986. The only exception was a remarkable decrease in the total intensity at one station near the central cone owing to the thermal demagnetization of the heated vent, which continued until the onset of the summit eruption.

Watanabe (1998) explained the reason why the inflation of Izu-Oshima volcano ceased for five years prior to the 1986 eruption as follows: magma began to rise through an open conduit and the excess pressure in the reservoir was balanced with the hydrostatic pressure from the magma column in the conduit, which resulted in the stoppage of inflation. Since the Curie point isotherm is estimated to lie at a depth of 5 km or so beneath Izu-Oshima volcano, the piezomagnetic effect associated with a pressure source (the Mogi model) below the Curie depth produces negative total intensity changes on the Earth's surface (Sasai, 1991). The same model with a similar arrangement of source position and Curie depth was applied to interpret the remarkable magnetic changes accompanying the upheaval of the resurgent domes in Long Valley caldera (Mueller and Johnston, 1991).

Will the decline of inflation occur prior to the coming eruption of Miyake-jima volcano? According to Watanabe's (1998) model, a mechanically stiff stable conduit is necessary for such a phenomenon. We have to take account of the fact that the principal mode of eruption on this volcano has been flank fissure eruption. The multiple reservoir system proposed by Amma-Miyasaka and Nakagawa (1998) seems to suggest that magma passes through different conduit(s) at each eruption. Because of insufficient data, the position of demagnetized area A in fig. 11 is most uncertain. We cannot fully rely on the same eruption scenario as Izu-Oshima volcano, in which the stoppage of inflation could be a mid-term precursor to the eruption.

In conclusion, electromagnetic observations on Miyake-jima volcano from 1995 to 1999 provide us with some new information on the magma plumbing system and its related phenomena:

a) A new thermally demagnetized area ('E' in fig. 11) was detected within the volcano for the first time since the 1983 eruption. This strongly suggests a new heat supply from depth.

b) Non-local and long-term variations in the total intensity are observed over Miyake-jima island, which seems to be related to the ongoing expansion of the volcano as revealed by GPS measurements.

c) Detailed resistivity structure by MT soundings gives good suggestions to the sources of anomalous magnetic changes.

d) Long- and short-span SP measurements are very useful to discriminate the natural magnetic noises originated from the meander of Kuroshio ocean current.

NOTE ADDED IN THE PROOF

Miyake-jima volcano erupted on July 8, 2000. Its activity started on June 26 with swarm earthquakes at a depth of several km below the summit, which was followed by a possible intrusive event beneath the western sea floor together with the shrinkage of the volcano edifice. The July 8 event was a phreatic explosion, which resulted in a large amount of depression in the summit Hatcho-Taira caldera. A circular area of 1 km in diameter fell down to a depth of 200 m from the caldera floor, but with a very minor amount of ejecta (less than one hundredth volume of the sinkhole). The source position of this unusual event was regarded as the demagnetized area E in fig. 11. The sinkhole became deeper to a depth of 250 m above mean sea level and was enlarged to 1.5 km in diameter until early September. Phreatic and phreato-magmatic explosions took place several times through a vent, which was just above the area E. Hence the demagnetized area E should have played a key role in the 2000 eruption of Miyake-jima volcano.

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