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Self-Potential Studies in Volcanic Areas (3)
—— Miyake-jima, Esan and Usu ——

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Abstract

Self-potential (S.P.) measurements exhibit that the large and positive S.P. anomaly is observed on the summit area of Miyake-jima volcano, while the significant anomaly related with the volcanic activity is not found on Esan volcano. A repeated measurement of the S.P. field on Usu volcano reveals the large and positive anomaly has been maintained during this decade. Different aspect of the S.P. fields probably depends on the differences in the hydrothermal system of each volcano.

1. Introduction

Recent advance of experimental and theoretical studies reveals that large self-potential (S.P.) anomalies in volcanic and geothermal areas, sometimes above several hundred mV, could be attributed to the electrokinetic effect due to hydrothermal circulation within a porous media. Therefore, the study of the S.P. anomalies provides valuable insights into dynamic aspect of the geothermal systems in volcanoes. From this point of view, S.P. measurements have been made, for example, on Soufrière (Zlotnicki et al., 1994a), Piton de la Fournaise (Zlotnicki et al., 1994b), Unzen (Hashimoto and Tanaka, 1995), Usu, Hokkaido Komaga-take and Me-akan volcanoes (Nishida and Tomiya, 1987; Matsushima et al., 1990). Our measurements reveal the positive potential anomalies, several hundred mV, having the large spatial wavelength (1~3 km) are mostly

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distributed on the whole area of the summit crater of Usu and Hokkaido Komaga-take, suggesting the existence of intensive circulation of the hot ground water within the edifices. On the other hand, we could not find any anomalies having large spatial wavelength on Me-akan. In this case, it is thought that the hydrothermal circulation of large size has not well developed within the edifice.

Recent eruptions occurred in 1977 at Usu and in 1929 and 1942 at Hokkaido Komaga-take, while Me-akan has no experience of essential eruption during the historic time except small phreatic ones in 1955 and 1956. Nishida and Tomiya (1987) and Matsushima et al. (1990) considered that the dormant period of three volcanoes might relate with the aspects of the S.P. anomalies: the shorter the period of dormancy, the larger the intensity and the spatial wavelength. In addition, the existence of highly permeable faults and fissures which activate further increase of the water flow rate must play an important role in the large amplitude of the S.P. anomalies on Usu and Hokkaido Komaga-take. However, the above-mentioned considerations are not neccessarily conclusive because the relation between the S.P. anomaly and the volcanic activity is not so simple. For example, the noticeable S.P. anomaly is observed on Hokkaido Komaga-take although the fumarolic gas temperature (~100°C) is considerably lower than that of Me-akan (~500°C). Therefore, we have to accummulate

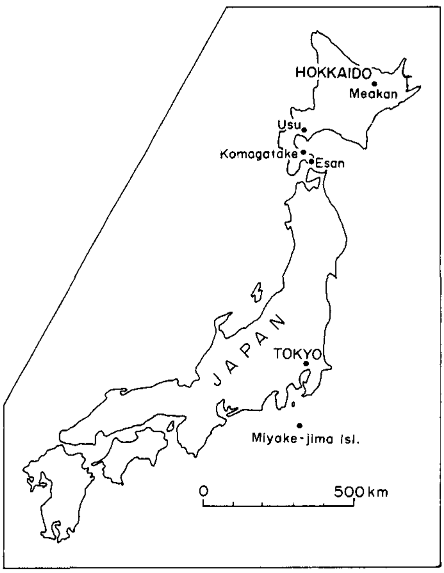


Fig. 1. Location map of the volcanoes.

further case studies of S.P. fields in order to establish the morphological insights of the S.P. anomalies in volcanic areas. In the present paper, we report the field data of the S.P. anomalies on Miyake-jima and Esan and the result of repeated measurement on Usu. The location map of the volcanoes is shown in Fig. 1.

2. Brief explanations of volcanic activities and the previous geophysical studies

2.1. Miyake-jima volcano

Miyake-jima is one of the largest of the Seven Izu Islands, and is situated about 200 km south-southwest of Tokyo. The island, which is circular in outline measuring about 8 km in diameter, is a basaltic volcano consisting of a main stratovolcano, a central cone and a number of parasitic cones and craters. Literatures tell the thirteen eruptions from 1085 onwards. Of these, the earlier five eruptions in 1085, 1145, 1469, 1535 and 1595 have no detailed description. The recorded eruptions in 1643, 1712, 1763 and 1835 belong to the central eruption type, while those in 1811, 1874, 1940 and 1962 to the fissure eruption type (eg. Issiki, 1960 ; Miyazaki, 1984). The latest activity took place on October 3, 1983. A large amount of basaltic lavas and scoriae spouted from the south-southwest trending fissures on the southern flank.

The fumarolic activity had been found on the summit crater although the intensity is moderate (fumarolic temperature had been below 100°C). The activity significantly increased one month after the 1983 eruption (Kagiyama et al., 1984). The VLF-magnetotelluric sounding at 17.4 kHz and the ELF-magnetotelluric sounding at 8, 14 and 20 Hz exhibit the low resistive layer (40 ~140 ohm-m) is seated at a few hundred meters below the summit crater (October, 1980). A repeated measurement on November, 1983 revealed the resistivity values of the layer showed further decrease to about 10 ohm-m one month after the 1983 eruption (Utada et al., 1984). Considering these evidences, Utada et al. (1984) concluded the hot ground water or vapor was supplied to the layer from the deeper part after the eruption.

2.2 Esan volcano

Esan is a stratovolcano located in the southernmost part of Hokkaido. The edifice is composed mainly of andesitic somma lava and lava domes. The summit crater is filled with pyroclastic flow deposits and debris avalanche deposits. In the southern part of the summit crater, there are many fumaroles spouting volcanic gas. Esan has never displayed the activity during the historic time except very small phreatic eruption in 1846.

Our measurement of fumarolic gas temperature on the summit crater showed about 200°C in maximum on August, 1993. The value has not changed since 1970 although the fumarole which shows the highest temperature has shifted occasionally (Nishida, 1972). We also made the horizontal electric resistivity sounding on August, 1993 using the direct current method (sounding depth is 100 m or so). The measurement was conducted along the A-B line as shown in Fig. 4. The result reveals the summit crater fill is low resistive (10 ~100 ohm-m) while the andesitic somma shows the high resistivity (~1000 ohm-m). The magnetic survey by Nishida et al. (1974) exhibits the somma lava is highly magnetized (7.5 A/m) in contrast with the crater fill (2.5 A/m).

2.3 Usu volcano

Usu is a stratovolcano located in the southwestern part of Hokkaido. The edifice is composed of basaltic somma volcano and crater fill including dacite domes. Paroxismal eruption took place on August, 1977 after 32 years dormancy. On the summit crater, numerous normal faults developed. The succeeding deformation is characterized by doming of a block bounded by U-shaped fault system. The doming activity gave rise to a new cryptodome, Usu-shinzan (US in Fig. 6), which grew to about 180 m in height. The intruded magma, which gave rise to such intensive crustal deformation, is infered in position beneath the new cryptodome, based on the vertical distribution of an earthquake-free zone (Okada et al., 1981).

Immediately after the 1977 eruption, a prominent geothermal field developed in the southwestern part of the summit crater. The total thermal discharge reached its maximum, 1.0×10^3 MW, in 1979 and had gradually decreased to 1.4×10^2 MW as of 1990 (Matsushima, 1992). The highest temperature of the volcanic gas from I-crater (I in Fig. 6) is nearly 500°C as of 1995.

Audiofrequency magnetotelluric sounding in the 8-1700 Hz frequency range displays well defined high resistive zones (HRZ) within the low resistivity crater fill. The noticeable HRZ is distributed on the considerably narrow zones along the faults where are high ground temperature zones (Ballestracci and Nishida, 1987). HRZ is interpreted as being due to rising steam through visible or latent fractures because the high temperature steam must dry the surrounding rocks; consequently the rocks become highly resistive. On the other hand, the low resistivity crater fill can be explained by the presence of ionized water which prevents upward flow of steams.

3. The results of self-potential mapping

3.1 Miyake-jima volcano

We made the S.P. measurements on October, 1990 and on April, 1991 on the summit crater floor and along a travers line (NEN-SWS) crossing the Miyake-jima island (Fig. 2). The observed values are plotted along the traverse line as shown in Fig. 3a. The values are represented by the relative ones to the tentative reference point. The terrain-related S.P. fields are clearly seen on the northeast and southwest foots of Miyake-jima: the relation between the S.P. and the altitude is 1.5 mV/m and 0.86 mV/m, respectively. The difference between both values may be due to the difference of the topographic gradient, indicating the larger flow rate of the near surface ground water along the steeper topography. Besides these terrain effect, a relatively positive anomaly is noticeably found on the central part of Miyake-jima volcano and must be the most important one related with the thermal process of Miyake-jima. Large amplitude amounting to about 700 mV and a trapezoidal shape of the anomaly pattern (sharp increase in both sides and rather flat on the crater floor) are the most significant feature of the present survey. Fig. 3b shows the contour map of a part of the major anomaly on the summit crater floor. The pattern of contours is unexpectedly not concentric but crescent. The concentric pattern may be disturbed by a negative anomaly due to the terrain effect of the central

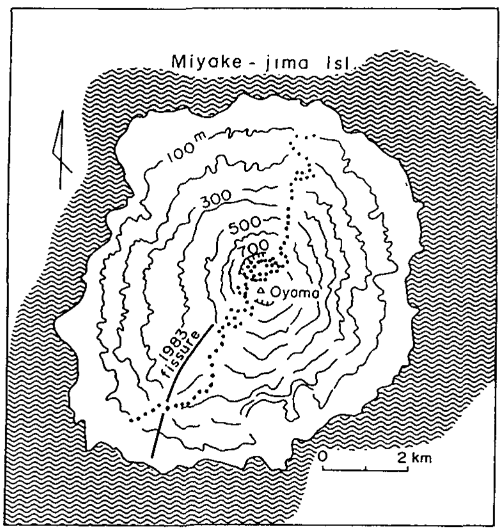
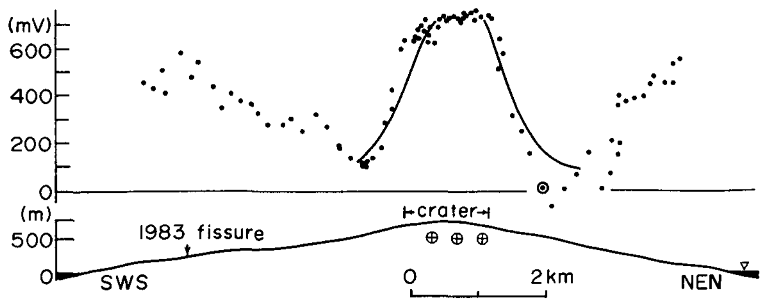
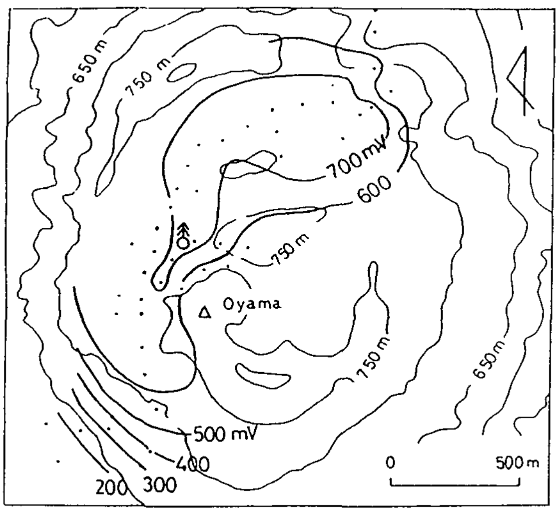


Fig. 2. The topographic map of Miyake-jima volcano and the S.P. survey stations.



(a)



(b)

Fig. 3. a) The S.P. anomalies on Miyake-jima volcano along the traverse line (NEN-SWS) shown in Fig. 2. The S.P. field is represented as the relative value to a tentaive reference one (0 mV) showed by double circle. Solid curve represents the calculated potential field caused by three positive point charges having the same and arbitrary intensity (⊕). b) Contour map of the S.P. distribution on the summit crater. Contour interval is 100 mV.

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The curve-matching technique is sometimes used for interpreting the observed S.P. anomaly on the basis of a point charge or some specific geometric body model. Obviously, the model does not define the mechanism of generation of the anomaly. However, it may be valuable to infer the source depth. A model, composed of horizontally distributed three positive charges with the same and arbitrary intensity, can interpet the major anomaly of Miyake-jima as shown in Fig. 3a. The source depth from the cratrer floor is calculated as a few hundred meters or so and is well correlated with the upper depth of the low resistive layer which is thought to be a water saturated layer (Chapter 2). Summarizing these evidences as well as the geothermal activity, it can be concluded that the positive S.P. anomaly is mainly originated from the electrokinetic effect due to the intensive hydrothermal circulation.

On the 1983 fissure, a small-scale positive S.P. anomaly (about 100 mV) is found. However, the electric potential values were fluctuated during the procedure of measurement in this region. This may be due to the inadequate electric contact between the electrode and the dry ground surface covered by permeable scoria deposits. Therefore, we do not conclude at present whether the anomaly is related with the 1983 activity.

3.2 Esan volcano

We measured the S.P. fields on August, 1993. The measurement points and the contour lines of the S.P. anomalies are drawn on the topographic map as shown in Fig. 4. Although the area surveyed is unfortunately limited, we may be able to delineate the general tendency of the S.P. anomalies on Esan: the contours show a concentric pattern. The cross-section of the anomalies in Fig. 5 reveals that the negative anomalies with narrow width are found on the north and south flanks. The anomalies are exactly distributed on the somma lava which is highly resistive and highly magnetized. Therefore, the origin of the anomalies must be closely related with the existence of the somma lava itself, although the detailed reason is not yet understood. Besides these negative anomalies, we cannot find any ones on the summit crater floor even in the fumarolic area.

3.3 Usu volcano

We made the repeated measurement of the S.P. field on Usu on October, 1994 following the 1983, 1985 and 1987 measurements. In the previous paper (Matsushima et al., 1990), we tentatively concluded that the decrease of the S.P. anomaly, about 50 mV, from 1983 to 1987 related to the recent decrease of the thermal energy release from the Usu edifice. However, the 1994 measurement reveals that general feature of the anomaly is almost the same as that in 1983 as shown in Fig. 6. It is concluded, therefore, the above-mentioned decreasing tendency of the S.P. anomaly is apparent and the spatial wavelength and the

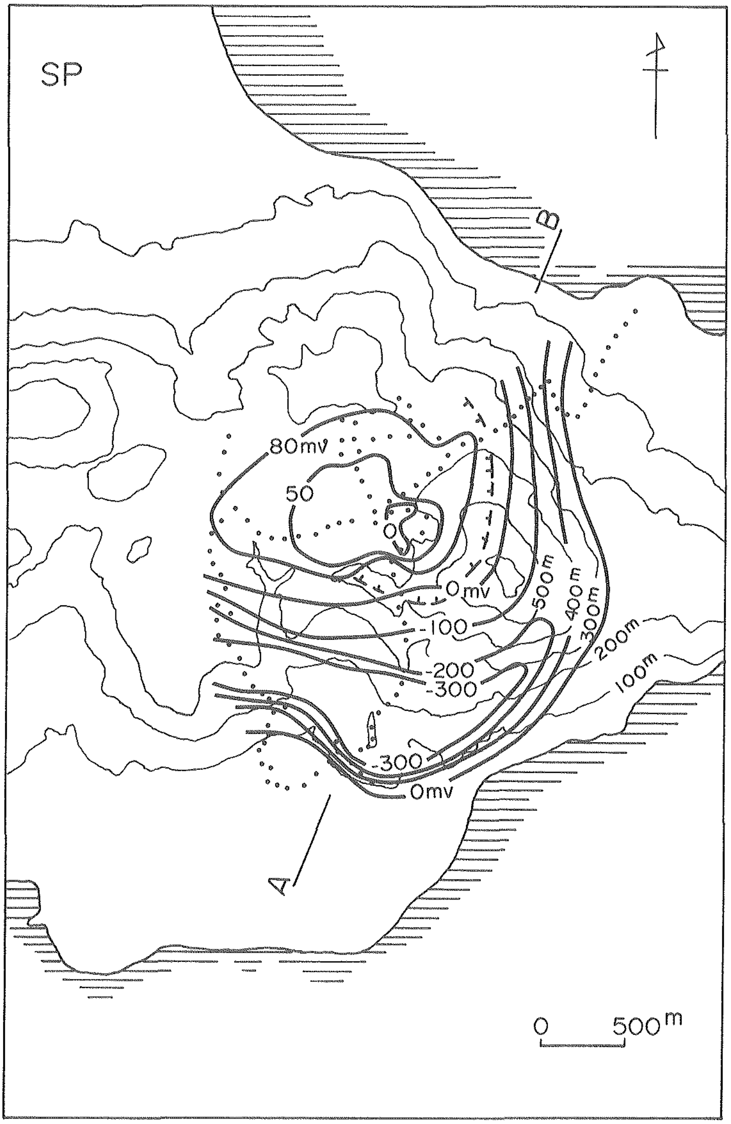

Fig. 4. Topographic map of Esan volcano (contour interval: 100 m), survey stations and contour map of the S.P. distribution (contour interval: 100 mV).

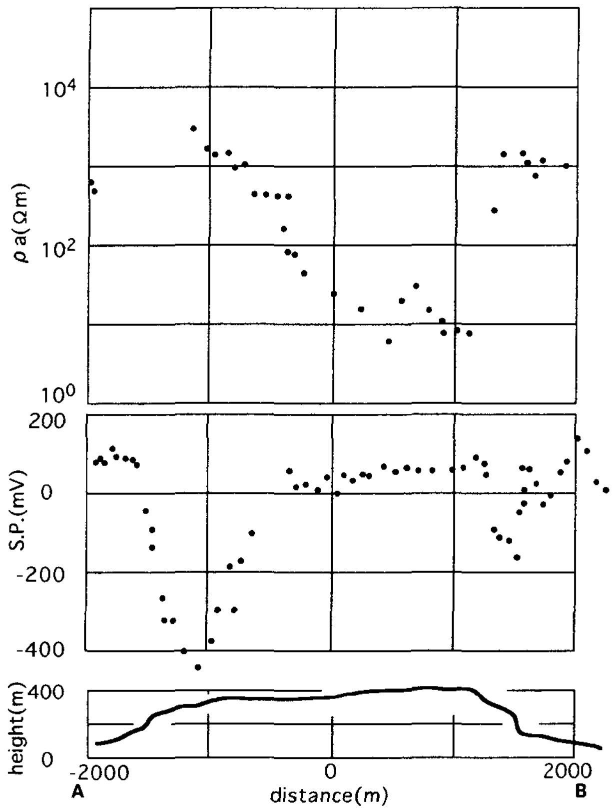

Fig. 5. The S.P. anomaly and apparent resistivity values on Esan volcano along the profile A-B shown in Fig. 4.

amplitude of the anomaly have been maintained during this decade. A positive point charge model gives the source is seated at a depth of a few handred meter beneath the crater floor as shown in Fig. 6.

4. Discussions

Prior to discussions, we present the basic data related with the S.P. anomalies of volcanoes concerned in Table 1 and Fig. 7 : rock types, existence of fissure and/or fault, fumarolic gas temperature and the history of eruptions. The high S.P. anomalies having the large spatial wavelength are mostly distributed on the summit crater of Miyake-jima as well as Usu, Hokkaido Komaga-take. It is clear that the appearance of the anomalies does not depend

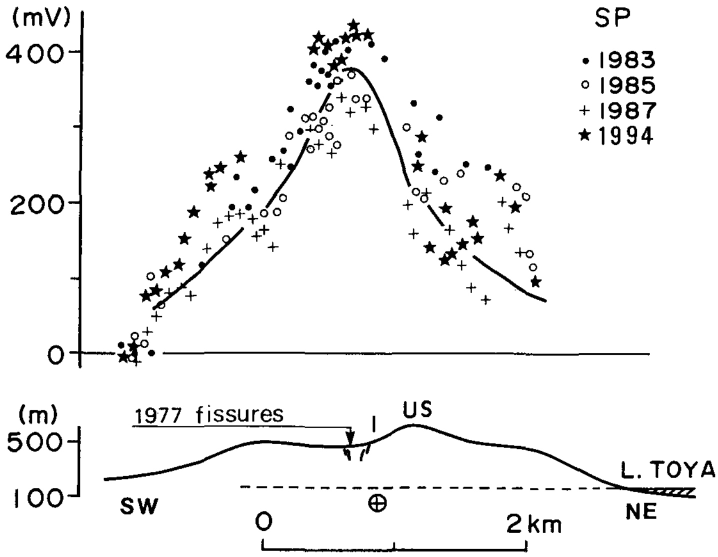

Fig. 6. Temporal variation of the S.P. anomaly along a profile crossing the NE-SW direction of Usu volcano. Topographic profile is also shown. Solid curve represents the calculated potential field caused by a point charge having the arbitrary intensity (⊕).

Table 1. Rock type, time of recent big or middle class eruption, existence of fissure and/or fault, temperature of fumarole and S.P. anomaliy are shown for volcanoes studied.

Volcano	Rock Type	Recent Big Eruption	Existence of Fissure or Fault	Fumarolic Temperature	Remarkable S.P. Anomaly
Usu	dacite	1977-1978	○	~500°C	○
Hokkaido Komaga-take	andesite	1942	○	~100°C	○
Miyake-jima	basalt	1983	○	<100°C	○
Me-akan	andesite	×	×	~500°C	×
Esan	andesite	×	×	~200°C	×

on the rock type of the volcanoes as shown in Table 1. Among many possible source mechanisms, the electrokinetic effect due to intensive upwelling of the hot ground water is a convincing interpretation because the high potential zones are commonly related to the high ground temperature zones in these volcanoes. In addition, the existence of the highly permeable fissure and/or fault, which activates further increase of the water flow rate, must play an important role in

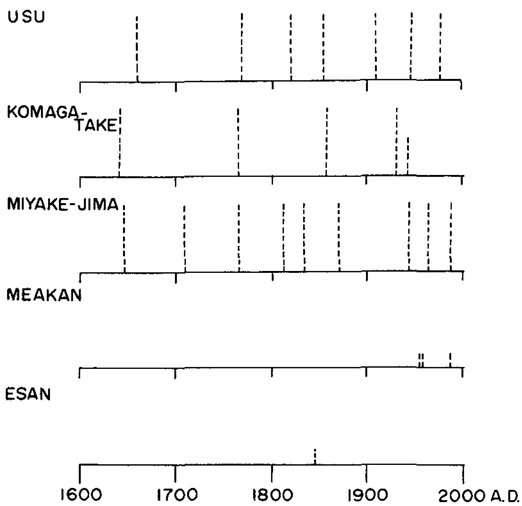

Fig. 7. History of volcanic eruptions of Usu, Hokkaido Komaga-take, Miyake-jima, Me-akan and Esan volcanoes. Magnitude of the eruptions is classified by three ranks as shown by the length of the dashed lines.

the large amplitude of these volcanoes.

However, the appearance of the S.P. anomaly does not simply correlated with the geothermal state of each volcano : 1) why the major S.P. anomaly has been maintained during this decade in spite of the fact that the thermal energy release has decreased in Usu? 2) Why the noticeable S.P. anomalies are observed on Hokkaido Komaga-take and Miyake-jima although the fumarolic gas temperature is considerably lower than that of Esan and Me-akan? Then, we propose speculative considerations to solve these problems as follows:

The formation of a cryptodome after the 1977 eruption proofs the existence of the viscous dacitic magma at a shallow depth of Usu. The remnant magma has been sorrounded by super-heated steam because the highest temperature of volcanic gas is nearly 500°C as of 1995. The surrounding liquid ground water exerts a hydrostatic head on the dry steam zone and causes a pressure gradient that forces the steam upward. The upward transported steam is replaced by vaporization of ground water that flows into the dry steam zone; that is, hydrothermal circulation takes place. This system of the hydrothermal circulation may have been maintained stationally during this decade because the volcanic gas temperature has exceeded the boiling temperature of water. The thermal energy release by the fumarolic activity may have been decreased by choking up of the near surface fracture due to argillization accompanied by hydrothermal alteration (Zlotnicki, 1994a), although the fumarolic activity is still active (Matsushima, 1992). Therefore, the cooling process of Usu has proceeded through the both factors of intensive hydrothermal circulation and fumarolic activity.

It is thought that the basaltic magma related with the 1983 eruption of Miyake-jima had already drain-backed to depths when we adopt an analogous model with Oshima volcano (Ida et al., 1988). The remnant magma of the Hokkaido Komaga-take is not found at shallow depth by a magnetic prospecting (Michiwaki et al., 1995). It is, therefore, reasonable to consider that the hot volcanic gas from relatively deep-seated magma intrudes into the liquid water-bearing volcanic edifices to drive the intensive hydrothermal circulation; consequently, the large S.P. anomalies are generated in these volcanoes. The hydrothermal circulation must work to prevent the uprize of fumarolic gas above the boiling temperature of the water at shallow depth (~100°C). Therefore, it can be assumed that the hydrothermal circulation is predominant in the magma cooling process of Miyake-jima and Hokkaido Komaga-take.

Heat source (or hot magma) is unlikely at shallow depth of Me-akan when we consider the dormant period of volcanic activity as shown in Fig. 7. Therefore, it is reasonable to consider that the aquifer does not well developed within the volcanic edifice and super heated gas is directly transported from the deeper part to the surface through the narrow vent (fumarolic gas temperature exceeds 500°C as of 1995). In addition, the super heated gas itself has not ability to transport the electric charge (Tyrand and Marsden, 1985). These may be the reasons why no remarkable S.P. anomaly can be observed on Me-akan. The active discharge of high temperature volcanic gas may be dominant in the thermal process within the edifice of Me-akan in contrast with the cases of Miyake-jima and Hokkaido Komaga-take. However, we cannot exclude the hydrothermal circulation at depths beneath Me-akan. The S.P. anomaly caused by such circulation may be undetectable by the present survey because the anomaly have the longer spatial wavelength than the measurement area of the present survey.

The same situation as Me-akan is considered in Esan because of its long dormancy of volcanic activity and super heated fumarolic gas temperature. However, another reason is also possible to interpret the negligible S.P. anomaly on the summit crater. The hot ground water, broken-out from the fumarolic spot on the summit crater, shows significantly low pH value of 1.7 (Katsui et al., 1978). A laboratory experiment by Ishido and Mizutani (1981) reveals that the ζ-potential depends on the pH value of an aqueous solution: the lower the pH

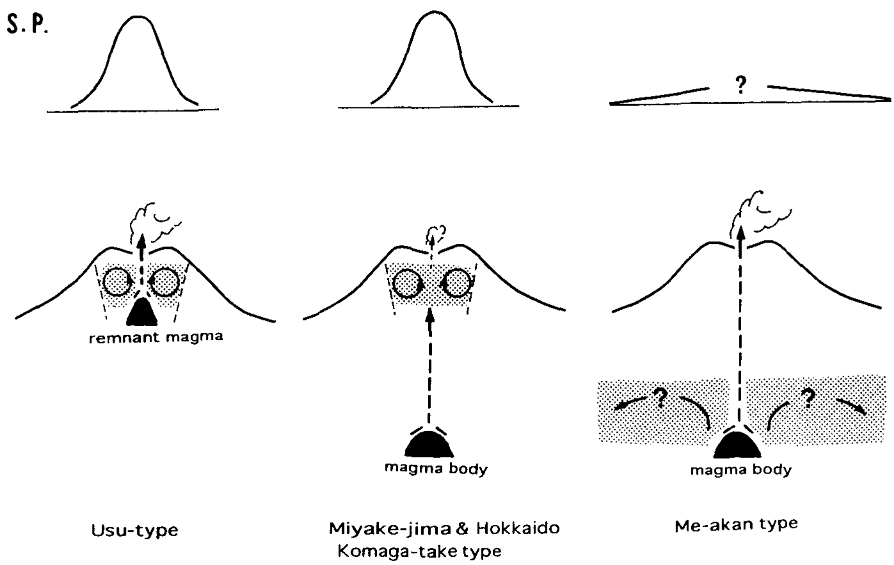

Fig. 8. Conceptual models of the geothermal system of volcanoes. Solid arrows represent the hydrothermal circulation, while dashed arrows indicate the volcanic gas flow. Shaded part shows the assumed aquifer.

value, the lower the absolute value of the ζ-potential. The low pH value, that is, the small electrokinetic coefficient leads that the hydrothermal circulation, if any, cannot generate the significant S.P. anomaly. Then, either reason is likely in the case of Esan.

Summalizing the above-mentioned discussions, we can draw schematic models of geothermal system for the studied volcanoes as shown in Fig. 8.

5. Conclusions

1. Large and positive S.P. anomaly was observed on the summit area of Miyake-jima volcano as well as Usu and Hokkaido Komaga-take volcanoes. It is interpreted that the anomalies are mainly caused by the electrokinetic effect due to upwelling of the hot ground water triggered by the shallow-seated remnant magma (Usu) and by the hot volcanic gas transported from the relatively deep-seated magma to the aquifer within the edifices (Miyake-jima and Hokkaido Komaga-take).

2. On the other hand, we have no significant S.P. anomaly on Esan volcano as well as Me-akan volcano although the volcanic gas temperature is higher

than that of Miyake-jima and Hokkaido Komaga-take. It is speculated that the aquifer does not well developed in the edifices of Esan and Me-akan. The low pH value (1.7) of the ground water is another possible reason of the negligible S.P. anomaly on Esan: low pH value, that means the small electrokinetic coefficient, leads that hydrothermal circulation, if any, cannot generate the significant S.P. anomaly.

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References

Ballestracci, R. and Y. Nishida, 1987. Fracturing associated with 1977-1978 eruption of Usu volcano, North Japan, as revealed by geophysical measurements. J. Volc. Geotherm. Res., **34**, 107-121.

Hashimoto, T. and Y. Tanaka, 1995. A large self-potential anomaly on Unzen volcano, Shimabara peninsula, Kyushu island, Japan. Geophys. Res. Lett., **22**, 191-194.

Ida, Y., K. Yamaoka and H. Watanabe, 1988. Model of volcanic activity associated with magma drain-back—Implication for eruptions of Izu-Oshima volcano after December, 1986—. Bull Earthq. Res. Inst., **63**, 183-200 (in Japanese with English abstract).

Ishido, T. and H. Mizutani, 1981. Experimental and theoretical basis of electrokinetic phenomena in rock-water systems and its applications to geophysics. J. Geophys. Res., **86**, 1763-1775.

Issiki, N., 1960. Explanatory Text of Geological Map of Japan (scale 1 : 50,000): Miyake-jima. Geol. Surv. Jpn., 1-85 (in Japanese with English abstract).

Kagiyama, T., K. Uhira, H. Yamamoto, H. Tsuji, T. Araki, N. Osada, E. Koyama, T. Takeda and T. Watanabe, 1984. Geothermal survey of the eruption of the Volcano Miyake in 1983. Bull. Volcanol. Soc. Jpn., **29**, S158-S174 (in Japanese with English abstract).

Katsui, Y., I. Yokoyama, Hm. Okada and T. Hakari, 1983. Esan: its volcanic geology, history of eruption, present activity and prevention of disaster. Committee for Prevention of Volcanic Disasters of Hokkaido, 1-99 (in Japanese).

Matsushima, N., 1992. Geothermal study on active volcano with special attention to the heat discharge process accompanied by the 1977 eruption of Usu volcano. D. Sci. Thesis, Hokkaido Univ., Sapporo (in Japanese).

Matsushima, N., M. Michiwaki, N. Okazaki, R. Ichikawa, A. Takagi, Y. Nishida and H.Y. Mori, 1990. Self-potential studies in volcanic areas (2)—Usu, Hokkaido Komaga-take and Me-akan—. J. Fac. Sci. Hokkaido Univ., Ser. VII, 8, 465-477.

Michiwaki, M.,N. Matsushima, R. Ichikawa, K. Yamaguchi, Y. Nishida, H. Oshima and H. Mori, 1995. Volcano-electromagnetic survey on Hokkaido Komaga-take. Bull. Volcanol. Soc. Jpn., **40**, (in Japanese with English abstract) (in press).

Miyazaki, T., 1984. Features of historical eruptions at Miyake-jima volcano. Bull. Volcanol. Soc. Jpn., **29**, S1-S15 (in Japanese with English abstract).

Nishida, Y., 1972. Seismometrical observation at Volcano Esan, Hokkaido. Geophys. Bull. Hokkaido Univ., **28**, 21-30 (in Japanese with English abstract).

Nishida, Y., F. Hayakawa and T. Wake, 1974. Geomagnetic survey and the investigation of fumaroles at Volcano Esan, Oshima Province. Rep. Geol. Surv. Hokkaido, **45**, 143-153 (in Japanese).

Nishida, Y. and H. Tomiya, 1987. Self-potential studies in volcanic areas (1)--Usu volcano —. J. Fac. Sci. Hokkaido Univ., Ser VII, 8, 173-190.

Okada, Hm., H. Watanabe, H. Yamashita and I. Yokoyama, 1981. Seismological significance of the 1977-1978 eruptions and the magma intrusion process of Usu volcano, Hokkaido. J. Volc. Geotherm. Res., **9**, 311-334.

Tyrand, C.K. and S.S. Marsden, Jr., 1985. The streaming potential of steam. Proc. Geothermal Resources Council Meeting, Hawaii in August 1985, 71-74.

Utada, H., Y. Sasai, I. Nakagawa, S. Koyama, Y. Ishikawa and Y. Hamano, 1984. Changes in the electrical resistivity associated with the 1983 eruption of Miyake-jima volcano. Bull. Volcanol. Soc. Jpn., **29**, S113-S124 (in Japanese with English abstract).

Zlotnicki, J., M. Feuillard and G. Hammouya, 1994a. Water circulation on La Soufrière volcano inferred by self-potential surveys (Guadeloupe, Lesser Antilles). Renew of volcanic activity? J. Geomag. Geoelectr., **46**, 797-813.

Zlotnicki, J., S. Michel and C. Annen, 1994b. Anomalies de polarisation spontanée et systèmes convectifs sur le volcan du Piton de la Fournaise (Ile de la Réunion, France). C.R. Acad. Sci. Paris, t. 318. Serie II, 1325-1331.