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# Self-Potential Studies in Volcanic Areas (1)
## —— Usu Volcano ——

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### Abstract

Self-potential fields are well mapped over a major part of Usu volcano. A positive anomaly developed over the mountain, 350～400 mV in magnitude, is the most significant feature of the present survey. Electrokinetic coupling effect due to intensive hydrothermal convection is a convincing interpretation of the anomaly because the high potential zone is closely related to a high ground temperature zone. High potential gradients observed near the crater rim are attributed to the effect of lateral resistivity variation between the somma volcano and the crater infill. Positive and negative anomalies of short wavelength are superimposed over the major anomaly. The former, distributed on the fumarolic spots, is also interpreted by electrokinetic effect. The latter is commonly observed on the lithic topographic highs and is possibly interpreted by local atmospheric electric potential variations at relatively poor conducting ridge. A repeated survey after two years reveals the decrease of nearly 50 mV in amplitude of the major anomaly. This may be an indication of secular variation of a hydrothermal system in Usu volcano.

## 1. Introduction

Usu volcano is a stratovolcano located in the southwestern part of Hokkaido, Japan. Occurrence of conspicuous crustal movements with earthquake swarms and forming lava domes and cryptodomes are characteristic features of its historic activities.

Paroxysmal eruption took place on August, 1977 after 32 years of dormancy (e.g. Katsui et al., 1978; Okada et al., 1981; Yokoyama et al., 1981). On the summit crater, numerous normal faults developed. The biggest one traversed the floor from Ko-usu lava dome to Ogariyama in a NW-SE direction (Usu-shinzan fault in Fig. 1). The fault extended towards the NW-SE direction beyond the crater rim (Kitabyobu-yama fault in Fig. 1). The succeeding defor-

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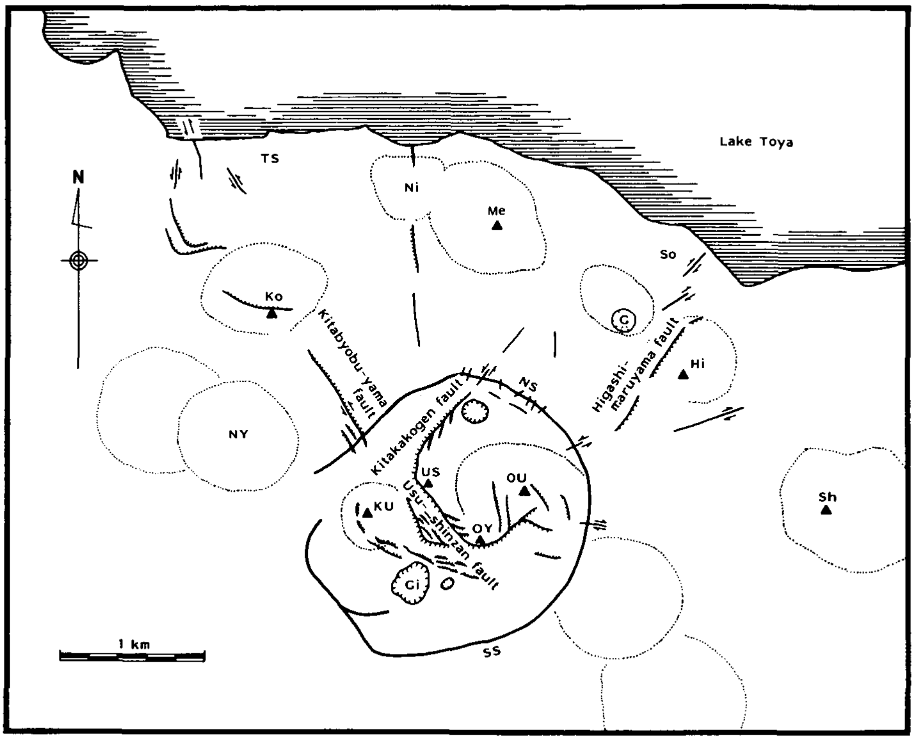

Fig. 1 Major faults produced during the 1977-1982 activity (after Katsui et al., 1985). Ko: Konpira-yama, TS: Toya spa, Ni: Nishi-maruyama, Me: Meiji-shinzan (Yosomi-yama), NS: North somma, SS: South somma, KU: Ko-usu, US: Usu-shinzan (New mountain), OY: Ogari-yama, OU: Oo-usu, Gi: Ginnuma crater, and dotted lines: lava domes and cryptodomes.

mation was characterized by doming of a block bounded by U-shaped fault system and continual thrusting of the block towards the northeast. A major fault scarp having NW-SE strike was elevated rapidly along the southwestern end of the block. Doming activity gave rise to a new cryptodome, Usu-shinzan, which grew to about 180 m in height. The intruded magma, which gave rise to such intensive crustal deformations, is inferred in position beneath the new cryptodome, based on the vertical distribution of an earthquake-free zone (Okada et al., 1981). Although seismic swarms and crustal deformations have ceased since 1982, discharge of the thermal energy is still active on the summit area. To trace the cooling process of the intruded magma may be one of the important themes of volcanology.

The use of the self-potential (SP) method to delineate the thermal state of volcanoes is a relatively recent application. For example, systematic survey of the SP field was carried out on Kilauea volcano, Hawaii. Results showed that not only were there obvious correlations between SP anomalies and thermal area but also that the anomaly magnitude was exceptionally large (Zablocki, 1976). Succeeding attempts have been made on several volcanoes such as Merapi (Bof et al., 1980), Piton de la Fournaise (Soudoplatoff et al., 1982), Stromboli (Ballestracci, 1982) and Etna (Massenet and Pham, 1985). In these cases, large and positive anomalies were also located over active fissure zones or fumarolic areas. Temporal and spatial measurements of the SP field, therefore, may prove to have an advantage of sensing the dynamic aspects of thermal systems in volcanic regions.

SP surveys were conducted on Usu volcano in 1983 and 1985. The objectives were 1) to establish the spatial distribution of the anomalies as fundamental data of Usu volcano; 2) to detect temporal variation in amplitude and pattern of the anomalies in two years; 3) to study the source mechanism of the anomalies.

## 2. Self-potential mapping

A reconnaissance survey of the SP field was made at Usu volcano on August, 1983. The equipments for measurements were composed of a pair of non-polarizing copper-copper sulfite electrodes and a high impedance voltmeter. Electrical contact to the ground was adequate in areas surveyed because sufficient moisture was always found on the surface. Figure 2 shows the topographic map of Usu volcano and the observation points. The southern part of the edifice was mainly surveyed. Measurements were carried out twice at several points on the summit crater to estimate closure errors. The errors did not exceed ±10 mV in all cases. One way measurements were made outside the summit crater. Consequently, the error estimation was not made. The contour map showing the distribution of the SP field is given in Fig. 3 with a contour interval of 50 mV. It is generally difficult to determine the reference station. The potential values are presented here as the relative ones in mV to a station away from the summit crater (double circles in Figs. 2 and 4). Dot-dashed contours represent the reference value while solid contours represent the positive anomalies.

The contour map reveals a rather simple pattern. A positive anomaly developed over the mountain, 350~400 mV in magnitude, is the most significant feature of the present survey. This major anomaly approximately shows a

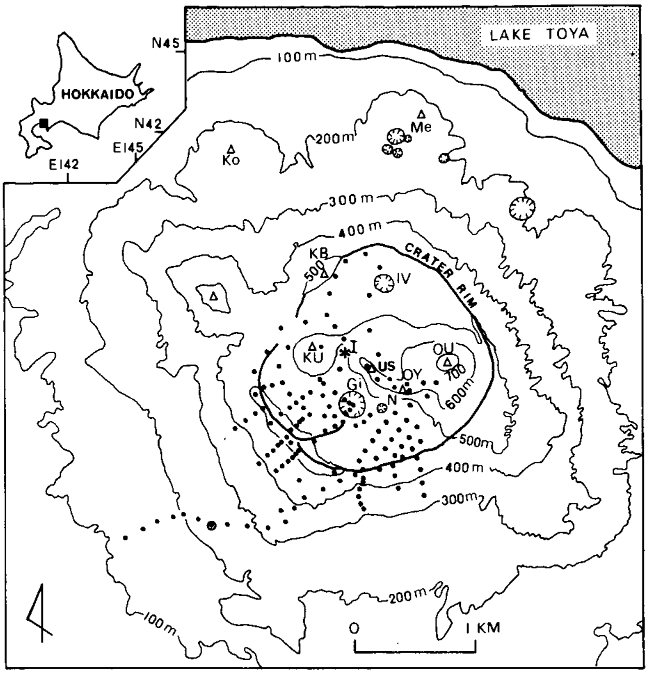

Fig. 2 Topographic map and survey stations in 1983. Double circle denotes the reference station. N : N-crater, I : I-crater, IV : No. 4 crater, and KB : Kitabyobu-yama hill.

concentric pattern centering at the southeastern part of Ko-usu lava dome, where the 1977 eruption took place. It is characteristic, however, that the contours are somewhat elongated to the NW-SE direction. The high potential gradients are observed near the southern crater rim. Negative and positive anomalies relative to the surrounding potential values are superimposed locally on the major anomaly. The former is intensive at the summit of Ko-usu and Oo-usu dacite lava domes while the latter, observed on the southern flank (H in Figs. 3 and 5), has small amplitude.

These initial findings encouraged additional studies, and on August, 1985, re-measurements were done. This survey confirmed a detailed picture of the SP fields over a major part of Usu volcano including Yosomi-yama (formed in the 1910 eruption) and Konpira-yama (the time of formation is unknown) cryptodomes. The observation points and the distribution of the anomalies are shown in Figs. 4 and 5, respectively. The 1985 survey shows that the elongated pattern of the major anomaly is characteristic in the contours above 250 mV while the anomaly below 250 mV is approximately concentric. High potential gradients were noticed not only near the southern crater rim but also near the northern rim. The amplitude of intensive negative anomalies at Ko-usu and Oo-usu lava domes respectively proved to be about −200 and −700 mV with respect to the surrounding potential values. A negative anomaly of short wavelength was newly detected on Kitabyobu-yama (about −200 mV), a hill composed of basaltic somma lava. Positive anomalies were found on Yosomi-yama and Konpira-yama cryptodomes.

## 3. Geothermal and magnetotelluric studies

Other geophysical data are available for interpretational support. Tomiya (1984a) measured the ground temperature at a depth of 1 m in 1983 as shown in Fig. 6. High ground temperature was mostly observed in the southwestern part

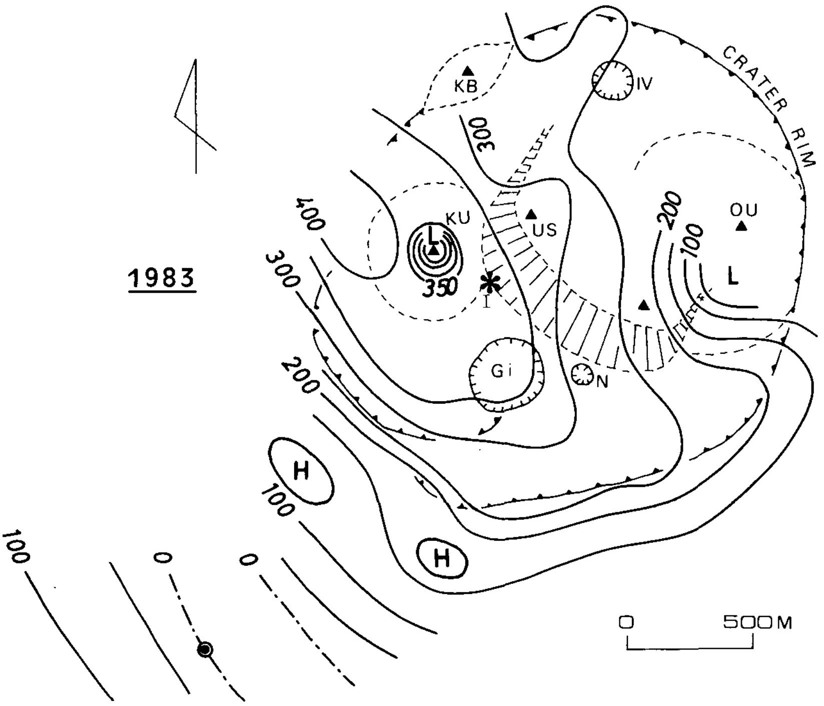

Fig. 3 Contour map of the self-potential distribution over the surface of Usu volcano. Contour interval is 50 mV. Dot-dashed contours represent the reference value while solid contours represent the positive anomalies.

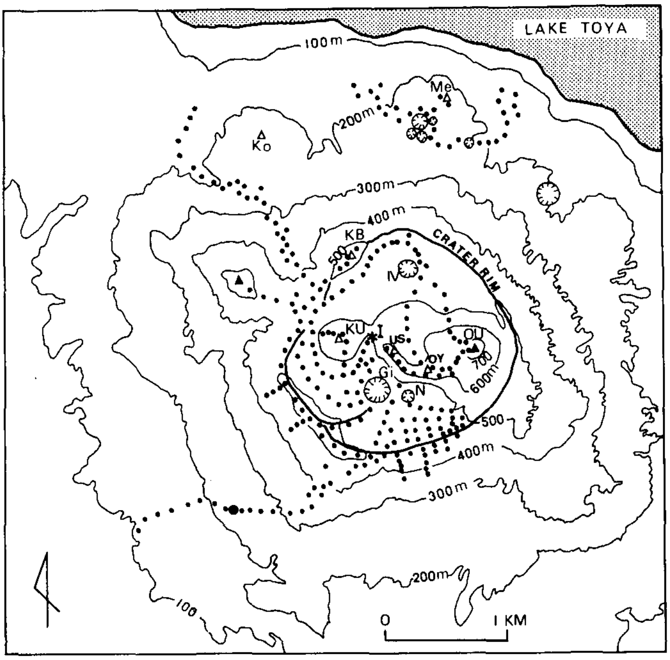

Fig. 4 Topographic map and survey stations in 1985. Double circle denotes the reference station.

of the summit crater. High temperature zone has predominantly a NW-SE trend along the Usu-shinzan fault. The crescent-shaped high temperature zones were detected along the northwestern crater rim including Kitabyobu-yama hill and along a small crater rim situated in the southwestern part of the summit crater. Several fumarolic spots having temperatures above 80℃ at a depth of 10 cm were also detected on a high temperature belt outside the southern crater rim (Fig. 6).

Temporal variations of geothermal activity in Usu volcano are shown in Fig. 7 (Sugoshi and Maekawa, 1981 ; Kagiyama et al., 1984 ; Tomiya, 1984b). The volcanic gas ejected from I-crater (Fig. 2) exhibits the highest temperature of about 700℃ as of 1985. Immediately after the 1977 eruption, a prominent geothermal field developed in Ko-usu-Shinzan area and the thermal energy has been transported to the atmosphere in the form of fumarolic plume. Simultaneously, steaming grounds developed over various places of the Usu edifice. The total thermal discharge reached its maximum, $1 \times 10^3$ MW, in 1979. Although it had gradually decreased to $3 \times 10^2$ MW as of 1983, the magnitude is several

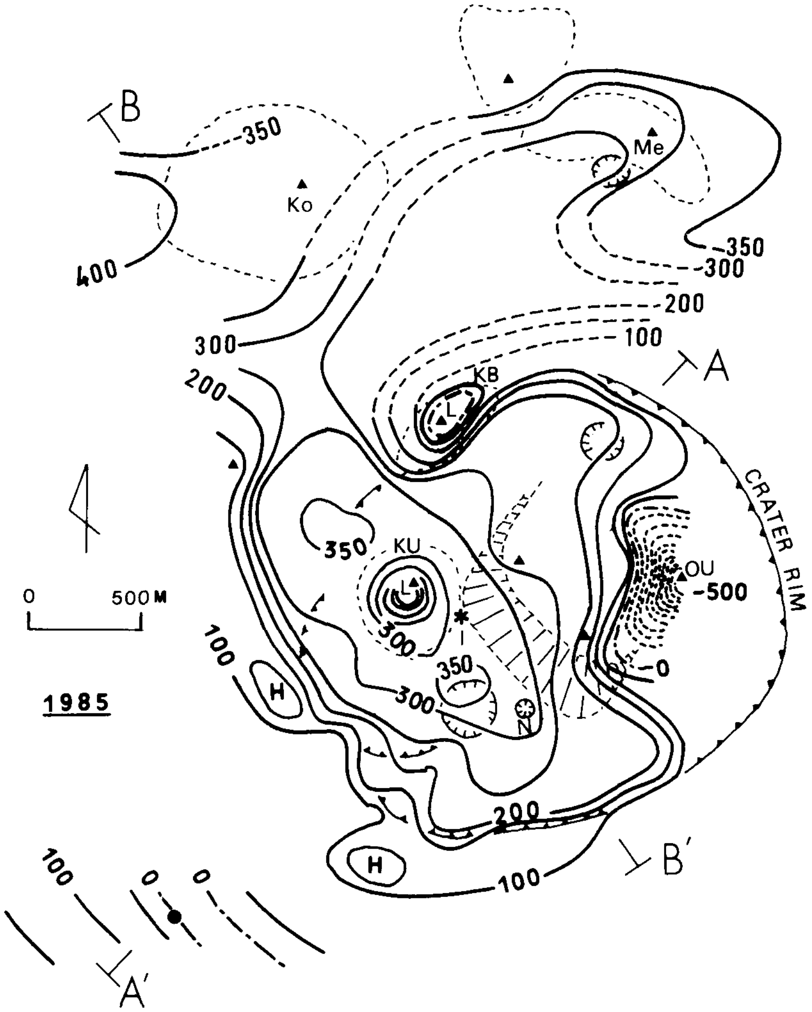

Fig. 5 Contour map of the self-potential distribution over the surface of Usu volcano. Contour interval is 50 mV. Dot-dashed contours represent the reference value while solid and dotted (around OU) contours represent the positive and the negative anomalies, respectively. Thin dashed lines show lava domes and cryptodomes as shown in Fig. 1.

hundred times as much as that before the eruption.

Audiofrequency magnetotelluric (AMT) soundings in the 8-1700 Hz frequency range were carried out by Ballestracci and Nishida (1987) on the summit crater of Usu volcano. The soundings displayed well defined high resistivity

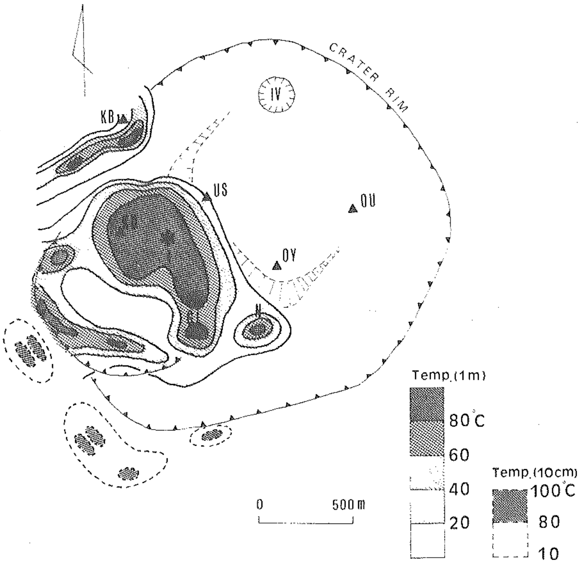

Fig. 6 Ground temperature distribution at a depth of 1 m (solid contours). Ground temperature at a depth of 10 cm is also shown by dashed contours. (after Tomiya, 1984 a)

zones (HRZ) within the low resistivity edifice. The noticeable HRZ is distributed along the Usu-shinzan fault and, hence, along a high ground temperature zone. 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 edifice can be explained by the presence of ionized water which prevents upward flow of steams.

## 4. Temporal variation of the self-potential field

Temporal variation of the SP field is the main interest of this study. Inspection of Figs. 3 and 5 exhibits that the anomalies of short wavelength as well as the major one have remained for these two years. Figure 8 indicates the variation in the potential distribution with time. The profile A-A′ is taken almost perpendicularly to the major axis of the elongated SP contours while the profile B-B′ is parallel to it (Fig. 5). Data within 300 m of each profile are projected on to the figures.

The SP profiles show an appreciable decrease of nearly 50 mV in two years

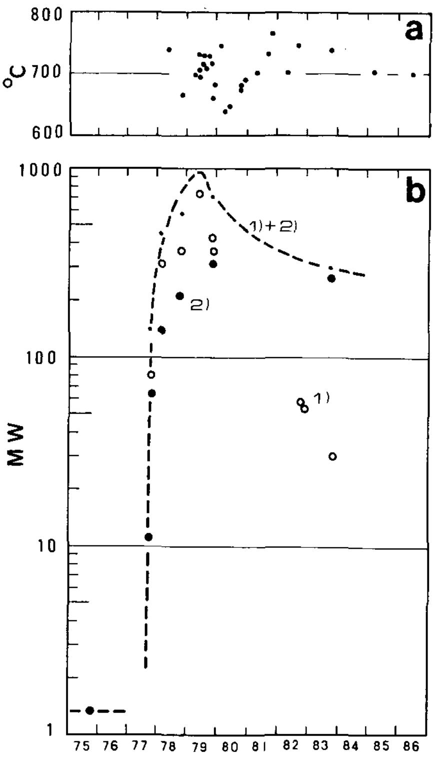

Fig. 7 a) Temporal variation of volcanic gas temperature at I-crater. b) Temporal variation of thermal energy release from the Usu edifice (after Tomiya, 1984b). Hollow circles denote the energy release in the form of fumarolic plume (1), while solid circles denote that from steaming ground (2). Small dots and dashed curve represent the total energy release (1+2).

(a decrease of a little over 10% of the total amplitude). On the other hand, the wevelength of the anomaly appears to be stable ; that is, the effective depth to the source does not noticeably change. Repeated surveys in Kilauea, Hawaii, revealed that some anomalies over thin eruptive fissures decrease in amplitude with time. The anomaly over 1974 eruptive fissure near Lua Manu Crater, for example, showed a dramatic decrease of about 300 mV in 6 months. Interpretation of this phenomenon was presented by Zablocki (1976) as rapid heat loss of a thin dyke at extremely shallow depths. In contrast to Kilauea volcano, the SP anomaly in Usu volcano would originate from a source at greater depths because the wavelength (about 3 km) is longer than that of the anomaly over the 1974 fissure in Kilauea (0.6 km). The decrease of the SP amplitude in Usu

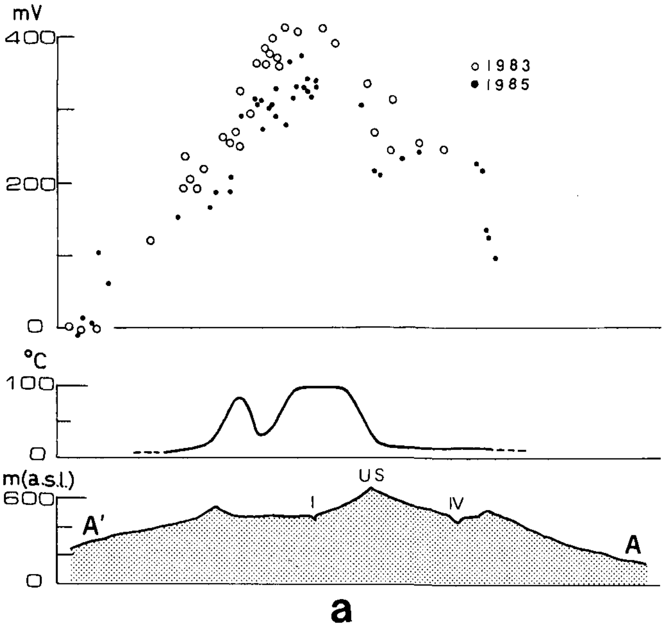

Fig. 8a Self-potential, ground temperature and topographic profiles along the A-A′ line in Fig. 5.

volcano may also relate to the recent gentle decrease of the thermal discharge. Further decline of the amplitude is anticipated as the thermal activity decays.

## 5. Discussions

### 5.1. *Interpretation of the major anomaly*

The reason of SP anomalies over volcanic regions is not fully understood. However, there are several possible explanations: electrochemical coupling, oxidation-reduction reaction, resistivity variation, thermoelectric coupling, electrokinetic coupling and so on. Among these mechanisms, electrochemical coupling and oxidation-reduction effects may be ruled out as the source mechanism of the positive anomaly amounting to 350~400 mV over the whole Usu edifice. Electrochemical potentials do not exceed about 20 mV in the ordinal geothermal area except in the special cases such as an alunite field (Nourbehecht, 1963; Corwin and Hoover, 1979). Oxidation-reduction effect caused by reactions between the volcanic gases and the ground water generates negative potentials and, hence, the effect cannot be a source mechanism for the

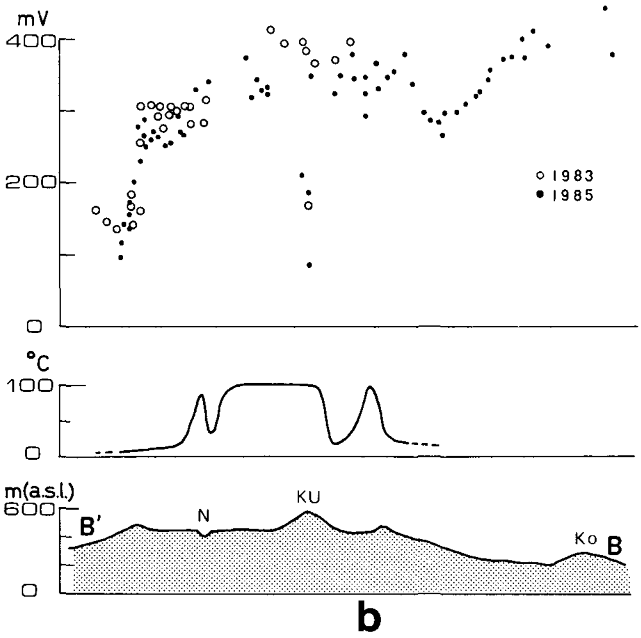

Fig. 8b Self-potential, ground temperature and topographic profiles along the B-B′ line in Fig. 5.

positive anomaly.

The elongated part of the major anomaly extends from the SE phreatic crater (N-crater in Fig. 2) to the NW, well beyond the crater rim, along the Usu-shinzan fault and the Kitabyobu-yama fault where are the high temperature and the high resistivity zones caused by rising steam. A clearer manifestation of such correlation is shown in Fig. 8 : the high potential anomaly well correlates with the high temperature zone except in the area covered with the crater infill which prevents upward flow of steams. It is evident, therefore, that the source mechanism of the anomaly is closely related to the heat-triggered phenomenon.

Thermoelectric coupling effect is a possible cause of the anomaly. A temperature gradient within the rocks ($\Delta T$) causes a corresponding voltage gradient ($\Delta V$) :

$$\Delta V = C\, \Delta T,$$

where $C$ is called the thermoelectric coupling coefficient. Calculated thermoelectric potentials due to a buried spherical body of elevated temperature (Nourbehecht, 1963 ; Corwin and Hoover, 1979) give 20 and 100 mV, respectively, for a realistic and a maximum values of the coefficient when we adopt $\Delta T$ of 750℃ which is an approximate temperature of the intruded magma of Usu volcano estimated by Tomiya (1984b). The calculated anomalies may partly interpret the observed one, although the spherical magma model is not necessarily realistic for Usu volcano and little knowledge is presently known about the behaviour of the thermoelectric coupling coefficient at high temperature. The greater part of the anomaly, however, should be interpreted by other source mechanism.

The motion of subsurface fluid is known to generate electric fields at the earth's surface. These streaming (or electrokinetic) potentials are developed by anion adsorption along the rock surfaces in the direction of the fluid stream lines (positive currents flow in direction of fluid flow). The streaming fields, $E$, are given by

$$E = \chi \Delta P,$$

where $\chi$ and $\Delta P$ are the electrokinetic coupling coefficient and the pressure difference along the flow path, respectively. Experimental data by Ishido and Mizutani (1981) exhibit that the electrokinetic coupling coefficient increases in magnitude with temperature for typical crustal rocks. Recent laboratory experiments by Tyrand and Marsden (1985) show that wet steam flow through a capillary tube also generates large electric potentials, although the flow of dry (superheated) steam results in no measurable streaming potentials.

Model calculations of streaming potentials associated with hydrothermal circulation show that positive SP anomalies up to 10～100 mV can be observed, for reasonable water flow rates of 0.3～3.0 m/y, over a hot zone where convective hot water is rising (Ishido, 1981). It is assumed in this case that the streaming potential coefficient varies, based on the experimental data, as temperature decreases from 200℃ to 100℃ along the flow of water. The calculated amplitudes are still insufficient to interpret the observed one in Usu volcano.

Near shallow magma, temperature rises in adjacent wall rocks and at some points the phase change from liquid water to steam produces a dry steam zone or superheated zone (Hardee, 1982). Heat transfer and fluid dynamics of the vertical dry steam zone adjacent to vertical magma body or vertical heated surface have been studied by Parmentier (1978) and Carrigan (1986). The surrounding liquid ground water exerts a hydrostatic head on the vertical 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 convection takes place.

The temperature at a boundary of liquid-vapour phase change can range from near the local boiling point (~100℃) at shallow depths to the critical temperature (374℃) at depths greater than 1 km.

Experiments with natural convection in a permeable medium (Dunn and Hardee, 1981) show the significant increase in heat transfer rates near the critical temperature (a factor increase of 70). Such a large increase in heat transfer rates also implies a significantly increased convective circulation. We can expect extremely amplified SP anomalies in this case because the streaming potentials increase in proportion to the water flow rate.

In an actual condition in Usu volcano, an exit gas temperature of about 700℃ at I-crater suggests the existence of dry steam zones. The low resistive edifice deduced from AMT soundings suggests that the ground water, which is necessary to generate the hydrothermal convection, is abundantly distributed within the edifice. These evidences enable us to infer that the significantly increased hydrothermal convection takes place within this region. In addition to this dynamic aspect of the thermal system, the highly permeable Usu-shinzan and Kitabyobu-yama faults may activate further increase of the water flow rate. Thus, the source mechanism of the SP anomaly over the whole Usu edifice can be mostly attributed to the streaming potentials up to several hundreds of mV, far greater than the potentials generated by thermoelectric or electrochemical coupling effect. An upwelling of ground water or wet steam controled by the faults may form the elongated pattern of the SP anomaly above 250 mV while the concentric one below 250 mV may be derived from hydrothermal convection triggered by the deep-seated magma column. However, it should be noted that the in-situ parameters such as the water flow rate, the electrokinetic coupling coefficient and so on are questions yet to be answered for quantitative interpretation not only for Usu volcano but also for other volcanes.

### 5.2 *High potential gradients near the crater rim*

The cause of the high potential gradients near the crater rim is unknown, but it is possibly attributed to a lateral variation in electric resistivity of medium. The SP field may be distorted by resistivity variations across contacts. A two-dimentional model calculation was made to check such a possibility, based on the same manner as Anderson and Johnson (1976). A simplified model, composed of buried dipolar current sources and vertical contact separating media of differing resistivity, was used here to simulate qualitatively the effect of lateral variation in resistivity (Fig. 9). Comparing two calculated potentials corresponding to an uniform model ($\rho_2/\rho_1=1$) and a differing resis-

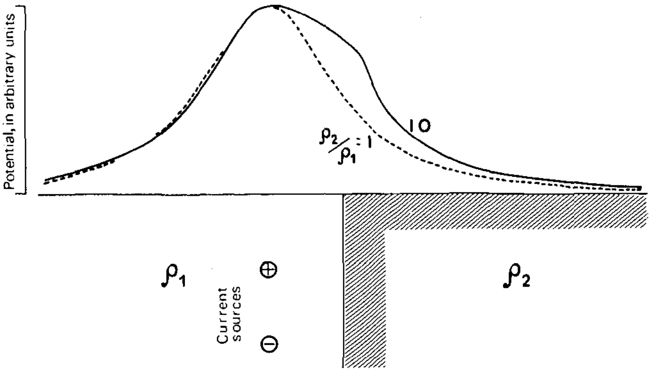

Fig. 9 Theoretical profiles calculated for a buried dipolar source near a vertical contact dividing media of differing resistivities, $\rho_1$ and $\rho_2$.

tivity model ($\rho_2/\rho_1=10$), the high potential gradients near the contact zone were well represented in the latter model.

Electrical prospectings by the use of direct current method (Watanabe et al., 1984) and AMT method (Ballestracci and Nishida, 1987) reveal that the resistivity of the southern somma of Usu volcano ($\gtrsim 100\ \Omega$m) shows a value of about ten times as much as that of the crater infill (a few to a few tens $\Omega$m). This result may be a favorable evidence for interpreting the high potential gradients near the crater rim by lateral variation in resistivity.

### 5.3. *Interpretation of the SP anomalies of short wavelength*

Several SP anomalies of short wavelength have remained stably in Usu volcano over a long period of time. Two positive anomalies with small amplitude exactly coincide in position with the fumarolic spots which are distributed on a high ground temperature belt outside the southern crater rim (Fig. 6). A geomagnetic prospecting (Nishida and Miyajima, 1984) exhibits that the southern rim of somma is situated about 200 m south of the present topographic rim. This phenomenon is an evidence of the existence of a buried horseshoe-shaped crater which has been thought to be formed by violent explosions several thousand years ago. Its southern opening might have been buried by subsequent eruptions to form the present somma. The high temperature belt closely coincides in position with such a buried crater rim. Fumarolic gases may be ejected through a contact between the somma lava and the crater infill. The weak positive anomalies are adequately interpreted by streaming potentials caused by the stational flow of wet steam. No similar surface manifestation is affiliated with the positive anomaly to the crescent-shaped high temperature zone situated along a small crater rim in the southwestern part of the summit crater.

Intensive negative anomalies are commonly distributed over the lithic topographic highs such as Oo-usu and Ko-usu lava domes (dacite rocks) and Kitabyobu-yama hill (basaltic somma lava). The occurrence of these anomalies are opposed to the expected positive anomalies due to the streaming potentials because considerable fumarolic activity is observed on these rocks, especially on Kitabyobu-yama hill. Negative anomalies caused by other source mechanism may cancel the positive streaming potentials.

SP anomalies appear to be predominantly negative in the vicinity of the upper portion of the ore bodies. Sulfides undergoing oxidation are well known as an origin of intensive negative potentials (Sato and Mooney, 1960). However, it is hard to say that Oo-usu, Ko-usu and Kitabyobu-yama are much abundant in sulfides relative to other areas within Usu volcano.

Topographic ridges sometimes give negative anomalies. Two different source mechanisms can be considered to interpret such a topographic effect. One involves negative streaming potentials on the summit area due to underflow from the summit to the foot of a mountain. This mechanism can be disregarded because the intensive underflow to generate potentials up to $-200 \sim -700$ mV is not realistic within the lava domes or the hill of Usu volcano. The other possibility involves local atmospheric electric potential variations at relatively poor conducting ridges (Brant, 1955). Dacite and basaltic rocks are probably more resistive than the crater infill with resistivity from a few to a few tens $\Omega \cdot$ m, although there is no available resistivity data for Oo-usu, Ko-usu and Kitabyobu-yama. The topographic effect of the latter type, therefore, is a possible interpretation of the intensive negative anomalies of short wavelength.

The contoured data don't adequately define the SP fields on Yosomi-yama. and Konpira-yama cryptodomes because the number of observation point is insufficient.

## 6. Summary and conclusions

Self-potential fields were well mapped over a major part of Usu volcano. The surveys yielded a number of interesting results. Detailed inspection of the major potential anomaly, predominantly developed over the mountain, reveals the following characteristics: 1) the anomaly, elongated to the NW-SE direction, is superimposed on the approximately concentric one; 2) high potential gradients are found near the crater rim. In addition to the major anomaly, positive and negative anomalies of short wavelength are found. The former is observed on the fumarolic spots while the latter is commonly observed on the lithic topographic highs.

Among many possible source mechanisms, electrokinetic coupling effect due to intensive hydrothermal convection is a convincing interpretation of the major anomaly because the high potential zone is closely related to a high ground temperature zone. The elongated anomaly may be strongly influenced by upwelling of ground water or wet steam controled by the permeable faults while the concentric anomaly may be derived from hydrothermal convection triggered by the deep-seated magma column. High potential gradients near the crater rim are attributed to the effect of lateral variation in resistivity of medium. Positive anomalies of short wavelength are also interpreted by electrokinetic phenomenon. On the other hand, negative anomalies on the lithic topographic highs are possibly explained by a kind of topographic effect: local atmospheric electric potential variations at relatively poor conducting ridge.

Although we present here the phenomenological causes to interpret the observed SP anomalies, more fundamental data on electrokinetic phenomenon, especially at high temperature, are needed to make a quantitative analysis. Furthermore, development of methods to investigate the in-situ electrokinetic coupling coefficient is also required.

A decrease of nearly 50 mV was observed in amplitude of the major anomaly within two years. Long-term observations of the potential fields could delineate the dynamic aspects of the thermal system in Usu volcano.

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