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Self-Potential Studies in Volcanic Areas (4) — An Attempt to Estimate the In-situ Value of the Electrokinetic Coupling Coefficient —

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Abstract

The large self-potential anomalies have been observed on many volcanoes. The anomalies are thought to be originated from the electrokinetic effect due to hydrothermal circulation within the volcanic edifices. The quantitative interpretation of the anomalies, therefore, provides an important information about the thermal process related with volcanic activities. It is important to know the in-situ value of the electrokinetic coupling coefficient for the quantitative interpretation of the anomalies. We made self-potential measurement in the Atosanupuri-Kawayu region as a field experiment to estimate the in-situ value of the coefficient. Subsurface structure and hydrothermal system, such as flow path, fluid volume flux, temperature, hydrouric permeability and so on, have been well studied by the hydrologists in this region. Combining these information with the observed self-potential field, we estimated the ζ-potential value within the range from -5 mV to -46 mV which is consistent with that of the laboratory experiment by Ishido and Mizutani (1981).

1. Introduction

The large self-potential (S.P.) anomalies, sometimes above several hundred mV, have been observed on many volcanoes such as Usu, Hokkaido Komagatake, Miyake-jima (Nishida and Tomiya, 1987; Matsushima et al., 1990; Nishida et al., 1996), Soufrière (Zlotnicki et al., 1994a), Piton de la Fournaise (Zlotnicki et al., 1994b) and Unzen (Hashimoto and Tanaka, 1995). The anomalies are qualitatively interpreted by the electrokinetic effect due to hydrothermal circulation which is closely related with the thermal process of the volcanic

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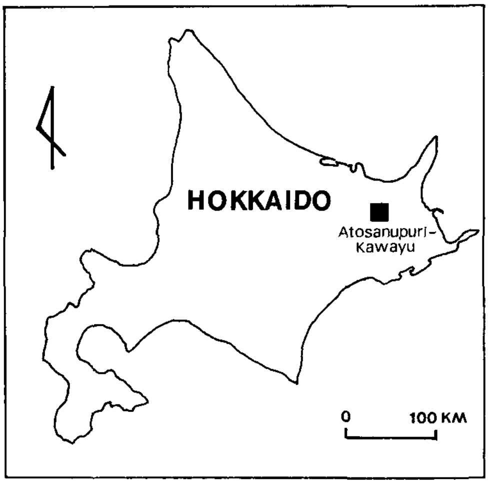

Fig. 1. Location map of the study site.

activity. In order to make quantitative interpretation of S.P. anomalies, we have to creer, at least, a problem: estimation of the in-situ value of the electrokinetic coupling coefficient. In the present study, we tried to estimate the in-situ value of the electrokinetic coupling coefficient through a field experiment in the Atosanupuri-Kawayu region, Hokkaido, Japan.

Atosanupuri volcano is located in the eastern part of Hokkaido (Fig. 1) and is a dacitic lava dome formed in the Atosanupuri caldera at the time of Holocene. A tephra-chronological study revealed the recent phreatic explosion took place several hundred years before (Katsui, 1962; Katsui et al., 1986). Subsurface structure and hydrothermal system of this region have been well studied by the hydrologists: this is the reason why we chose this region as an experimental field.

2. Brief explanations of volcano-hydrological setting

A geophysical investigation by Fukutomi et al. (1966) reveals that mixed phases of liquid and vapor uprise, and are separated at a shallow-seated cavity (less than 200 m in depth) beneath Atosanupuri volcano. The vapor phase directly ejects to the air while the liquid one becomes almost horizontal flow to Kawayu hot spring, 2 km apart from Atosanupuri. It is estimated the hot water of 118°C at the cavity is cooled down to 65°C at Kawayu hot spring.

Fig. 2 shows the schematic representation on mechanism of formation of

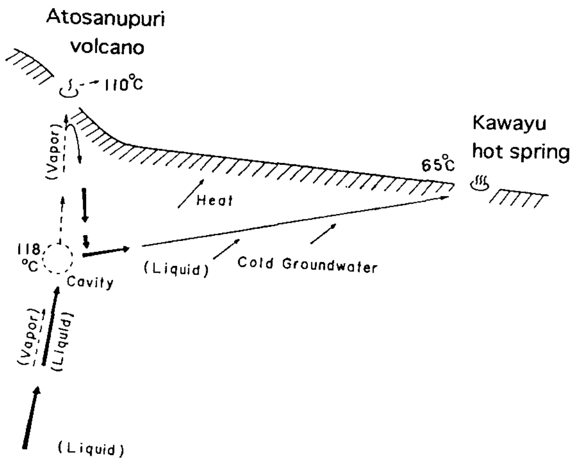

Fig. 2. Schematic representation on mechanism of formation of vapor and hot water in the Atosanupuri-Kawayu region (after Fukutomi et al., 1966). Dashed arrows represent the vapour phase while solid ones show the liquid phase.

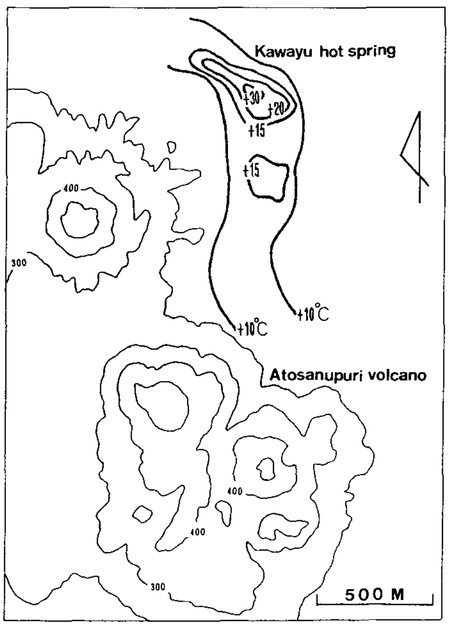

Fig. 3. Topographic map of the Atosanupuri-Kawayu region. Contour interval is 100 m. Horizontal distribution of ground temperature at a depth of 1 m is also shown (after Urakami et al., 1971). Hot ground water is assumed to flow at shallow depth beneath the narrow zone bordered by the higher ground temperature than 10°C.

vapor and hot water. It is thought the hot water flows within a nallow channel (horizontal width: 300 m or so) as shown in Fig. 3 because the high ground temperature (>10°C) and high conductivity (0.1~0.5 S/m) values distribute along a narrow zone from Atosanupuri-yama to Kawayu hot spring (Urakami et al., 1971).

3. Observed S.P. field and estimation of the electrokinetic coupling coefficient

We made a S.P. survey on June, 1993 in the Atosanupuri-Kawayu region. As the original data contains the east-west trend of long wavelength which is not interested in the present study, we eliminate this trend by the 1st order trend analysis and extract the horizontal distribution of the S.P. anomalies as shown in Fig. 4. Fig. 5 shows the relation between the S.P. value and the horizontal

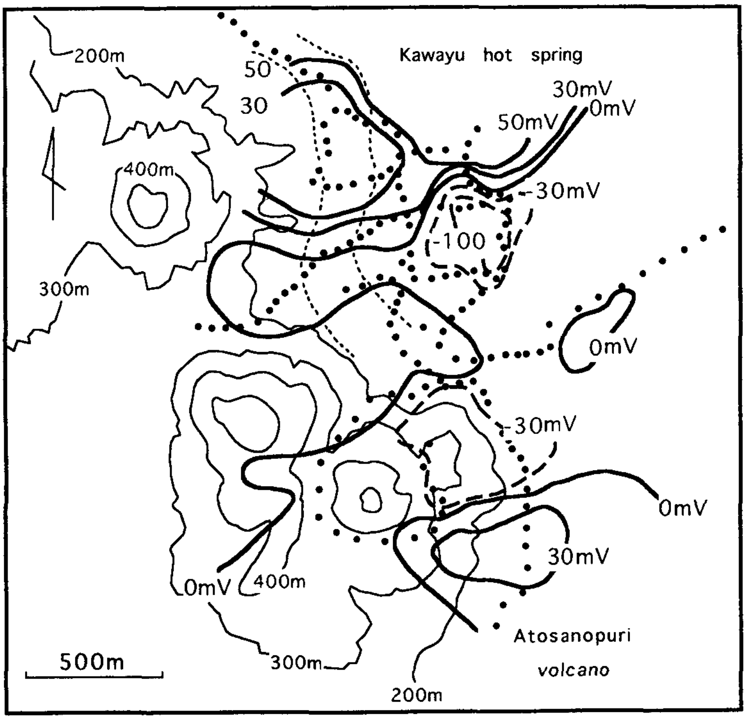

Fig. 4. Topographic map of the Atosanupuri-Kawayu region, observation points of the S.P. field and the contour map of the S.P. distribution in mV are shown. The assumed hot ground water flow path is bordered by two dashed curves.

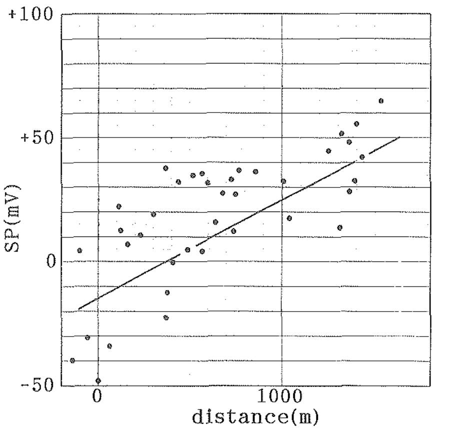

Fig. 5. The S.P. values against the horizontal distance between Atosanupuri volcano and Kawayu hot spring.

distance along the nallow channel zone. These figures reveal the S.P. anomaly tends to be higher in the Kawayu hot spring side, although the data are somewhat dispersed. Applying the linear approximation between the S.P. value and the horizontal distance, we can get the potential gradient (electric field) as 0.04 mV/m as shown in Fig. 5.

The general relations between the electric current density I and the fluid volume flux J, and the electric potential gradient $\nabla\phi$ and the pore pressure gradient ∇P are governed by

$$I = -\chi\sigma\nabla\phi - \frac{\chi\varepsilon\zeta}{\eta}\nabla P \tag{1}$$

$$J = -\frac{\chi\varepsilon\zeta}{\eta}\nabla\phi - \frac{K}{\eta}\nabla P \tag{2}$$

through Onsagar's reciprocal relations. σ, ε and η are, respectively, the electric conductivity, dielectric constant and viscosity of the pore fluid. χ and K are the porosity and permeability of the medium. ζ, the zeta potential, is the voltage across the Helmholtz double layer. The first term on the right-hand side in eq. (1) represents Ohm's law while the second term in eq. (2) represents Darcy's law. The first term on the right-hand side in eq. (2) is negligibly smaller than the second term in eq. (2) in the usual geologic conditions ($\chi\varepsilon\zeta/\eta \cdot \nabla\phi \sim 0$) (Ishido et al., 1989). In the steady state ($I=0$), the electric potential gradient $\nabla\phi$ is

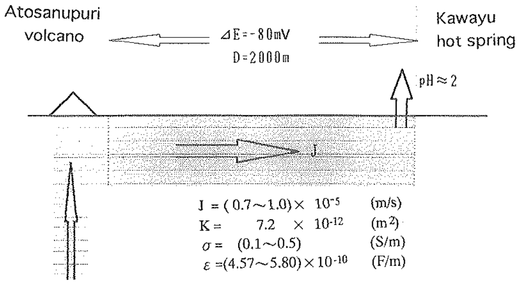

Fig. 6. A simplified model of hydrothermal system in the Atosanupuri-Kawayu region.

represented from eq. (1) as,

$$\nabla \phi = \frac{\varepsilon \zeta}{\sigma \eta} \nabla P \tag{3}$$

where $\varepsilon\zeta/\sigma\eta$ is called the electrokinetic coupling coefficient. Eliminating ∇P from eqs. (2) and (3), we get a relation between the electric potential gradient and the fluid volume flux as,

$$\nabla \phi \sim \frac{\varepsilon \zeta}{\sigma K} J \tag{4}$$

Simplifying the subsurface structure proposed by Fukutomi et al. (1966), the hydrological system of the Atosanupuri-Kawayu region is modeled as shown in Fig. 6. The electric potential gradient $\nabla \phi$ along the horizontal flow path is estimated as 0.04 mV/m in the present survey. The fluid volume flux J was measured by Fukutomi et al. (1966) as $(0.7 \sim 1.0) \times 10^{-5}$ m/s from the observation of the divergence of Kawayu hot spring. Urakami et al. (1971) obtained the permeability K by a hydraulic pumping test as 7.2×10^{-12} m^2 and the electrical conductivity σ by an electrical prospecting as $0.1 \sim 0.5$ S/m along the hot water flow path. For the dielectric constant ε, we used the value of the liquid water in this study because determination of the in-situ value is difficult at present. The temperature dependence of ε is governed by

$$\varepsilon = 78.54\ [1 - \alpha(T-25) + \beta(T-25)^2 - \gamma(T-25)^3] \times 8.854 \times 10^{-12} \tag{5}$$

where $\alpha = 4.579 \times 10^{-3}$, $\beta = 1.19 \times 10^{-5}$, $\gamma = 2.8 \times 10^{-8}$ and T is the temperature of the water in ˚C. Then, we can assume the value of ε as $(4.57 \sim 5.80) \times 10^{-10}$ F/m for the temperature range from 65˚C to 118˚C.

Thus, we can estimate the in-situ value of the ζ-potential, an important factor of the electrokinetic coupling coefficient. Substituting the abovementioned values of $\nabla\phi, J, K, \sigma$ and ε to eq. (4), the ζ-potential is estimated within the range from -5 to -46 mV.

4. Discussions

It is known that the ζ-potential strongly depends on pH of an aqueous solution, as well as temperature and electrolyte concentration (e.g. Ishido and Mizutani, 1981). They made detailed laboratory experiments to investigate pH dependence of the ζ-potential. The ζ-potential of orthoclase, albite, granite, granodiorite, andesite and gabbro in aqueous solutions of $10^{-3}N$ KNO_3 ranges from 0 mV to -30 mV for an appropriate value of pH ($\sim$2) in Kawayu hot spring (Fig. 7). These values of the ζ-potential seem to be slightly smaller in absolute values than those estimated from the present study. However, their experiments were precedured at a temperature of 45°C. Absolute values of the ζ-potential tend to be larger at higher temperature (Ishido and Mizutani, 1981). Considering this evidence, it can be safely concluded that the in-situ value of the ζ-potential by the present study is well consistent with the results from the laboratory experiments by Ishido and Mizutani (1981). In other words, the experimental results by them are significantly applicable to the actual field.

However, we have to say an important problem in the present study. As shown in Fig. 7, absolute value of the ζ-potential tend to be small as pH value becomes small. The ground water in the Atosanupuri-Kawayu region shows strong acidity as indicated by the small pH value ($\sim$2), suggesting generation of

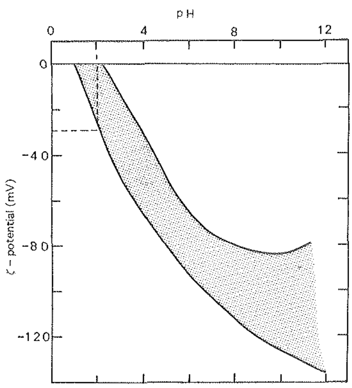

Fig. 7. The pH dependence of the ζ-potential for various minerals and rocks in aqueous solutions of 10^{-3} N KNO_3 (modified after Ishido and Mizutani, 1981). The data are ranged within the shaded part.

the S.P. field is suppressed. This implies our estimation of the in-situ ζ-potential contains certain amount of error. Therefore, we must try to accumulate the additional field data of the electrokinetic coupling coefficient. Further laboratory experiments about the electrokinetic phenomenon are also required. Quantitative discussions of the S.P. field must contribute to investigate dynamic aspect of the gethermal systems in volcanoes.

5. Conclusion

Subsurface structure and hydrothermal system of the Atosanupuri-Kawayu region have been well studied by the hydrologists. Using these information, we made an attempt to estimate the in-situ value of the electrokinetic coupling coefficient, especially the ζ-potential. The estimated ζ-potential ranges from -5 mV to -46 mV. The value is consistent with that of the laboratory experiment by Ishido and Mizutani (1981). We have to accumulate further field data of the electrokinetic coupling coefficient to quantify the S.P. anomalies in volcanic regions.

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