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Self-potential Measurements on Shinmoe-Dake, Kirishima Volcanic Group

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Abstract

We conducted self-potential (SP) surveys on Shinmoe-Dake, one of the active volcanoes in Kirishima volcanic group. The surveys cover an area of 1km × 1 km including the crater. One of the prominent features is a negative anomaly on the crater basin. The streaming potential caused by drainage of water from the crater basin is a promising candidate for a cause of the negative anomaly. We quantitatively verified the plausibility of the mechanism using seepage of the lake water and the permeability of the ground, which were estimated from the water balance of the crater lake.

Another prominent feature is positive SP anomalies on the eastern and southern slopes of Shinmoe-Dake. These positive anomalies lie over relatively low resistive regions revealed by a magnetotelluric survey. This fact suggests that the present positive anomalies are generated by the streaming potential accompanied by hydrothermal upflows, although there still remains uncertainty because we have no information on the ground temperature.

We also found positive patches of SP which were located at the fumaroles in the crater basin. However, they turned out to be rather small both in size and intensity after correcting for topographic effects. This suggests that hydrothermal activity just under the crater of Shinmoe-Dake is weak at present.

1. Introduction

The Kirishima volcanic group, located on the border between Miyazaki and Kagoshima prefectures, Kyushu island, Japan, consists of more than 20 small volcanoes. Shinmoe-Dake is one of the active volcanoes that belong to the Kirishima volcanic group. The stratovolcano has a crater about 750 m in diameter with a crater lake in its basin. There are some fissures on the western slope of the edifice which were formed during the eruption in 1959. Weak fumarolic activity exists in the crater basin and at the fissures (KAGIYAMA et al., 1979). The temperature of the fumaroles was higher than 200°C in the early 1980s. However, it has been lower than 100°C recently except during the small phreatic eruption in 1991 (KAGIYAMA, private communication). Studies on deposits and historical records show that each eruptive episode of historical activity of Shinmoe-Dake progressed from phreatic to magmatic and that the eruptions were frequently accompanied by pyroclastic flows and mudflows (IMURA and KOBAYASHI, 1991). Magnetotelluric surveys in the Kirishima volcanic area (KAGIYAMA, 1994a) have revealed that the ground resistivity in this area is generally low (∼a few Ω-m at the depth of a few hundred meters). This suggests that the shallow part of the Kirishima area is abundant in ground water.

The self-potential (SP) method, measurements of natural DC electric potentials on the ground, has been used since more than a century ago in the field of mining. However, application of the method to volcanic fields is relatively new. Previous studies of active volcanoes or geothermal regions such as Kilauea (ZABLOCKI, 1976), Yellowstone (ZOHDY et al., 1973) and Long Valley caldera (ANDERSON and JOHNSON, 1976), revealed that thermal zones were in most cases correlated with positive SP anomalies. However, as we will show in a later section, Shinmoe-Dake has a negative SP anomaly in its crater basin. In this paper we are going to clarify the mechanism which causes the negative SP anomaly. We will also discuss the other SP anomalies found on the volcano.

2. Self-Potential Measurements

We conducted SP surveys in November 1992, May 1993, and October 1993. The northern and eastern slopes of Shinmoe-Dake were explored in the first survey, the crater basin in second, and the area from the south to west in the last. Fig. 1 shows the distribution of survey points. We employed an electric cable 400 m long, a pair of $Cu\text{-}CuSO_4$ non-polarized electrodes and a portable digital voltmeter with internal impedance of more than 10 M-ohm. We removed surface soil with weeds or pebbles before we put an electrode on the ground. We took an average of the values obtained on at least three individual points for each site to eliminate anomalous potentials of very local origin. Scatter of values at each site did not exceed 10 mV in most cases.

We also conducted continuous monitoring of self-potential at several points on the western slope of the volcano from December, 1991. Only slight changes in SP as small as 10 mV were observed during 1992 and 1993. These changes are small compared to the intensity of anomalies in the target area. Therefore, we consider that the spatial distribution of SP in the target area has not changed during the period and combine the results of each survey to make a single SP map on Shinmoe-dake (Fig. 2).

3. Results

Fig. 2 shows the spatial distribution of SP on Shinmoe-Dake. In the crater

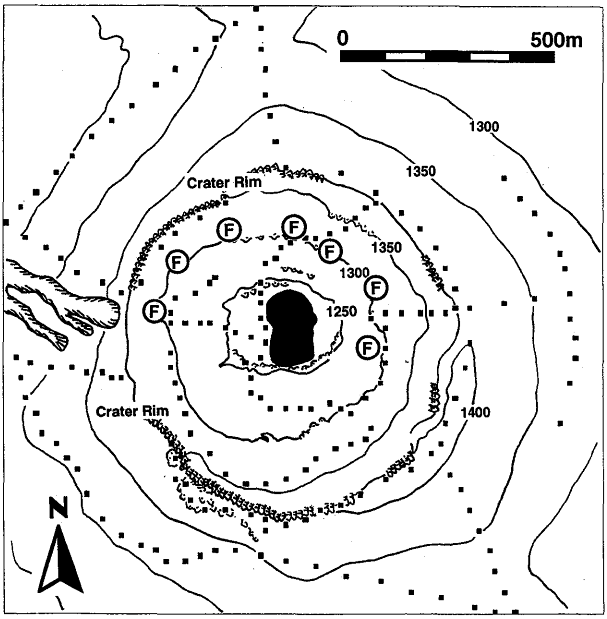

Fig. 1. The distribution of self-potential survey points on Shinmoe-Dake. Each square dot indicates a survey point. Topographic contour lines are given in units of meters. F in a circle shows the location of a fumarole. The crater lake is shown as a dark area at the center of the crater.

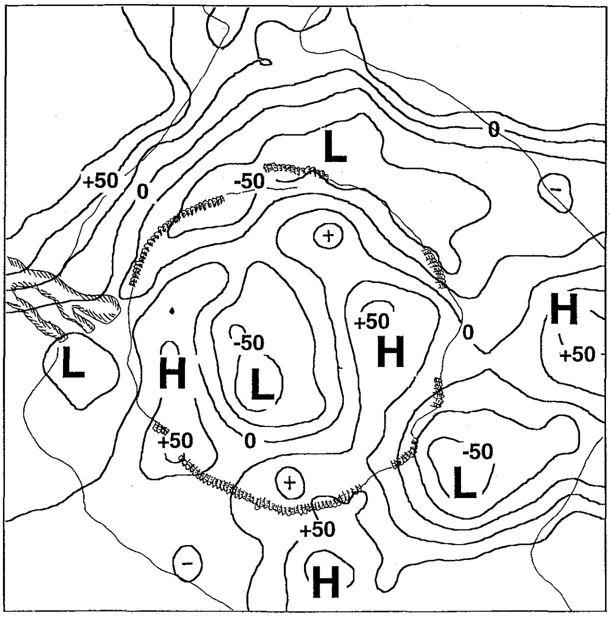

Fig. 2. Self-potential map (raw values before topographic correction) in the same area as Fig. 1. SP values are given in units of millivolts. The contour interval is 25 millivolts.

basin, a negative anomaly is located on the crater lake. Two positive patches surrounding the lake correspond to fumaroles. Outside the crater, we find high SP zones several hundred meters across on the southern and eastern slopes.

A trend of SP values corr領rated with topographic elevation can be seen, especially on the northern slope. As the topographic elevation becomes higher, the self-potential tends to be lower. In SP surveys in mountain areas we often encounter this kind of SP profile. ISHIDO (1989) explained that such "topographic effects" are caused by steady-state fluid flow owing to spatial variations in the elevation of the subsurface water table. Using the SP profile on the northern slope, where we can see a good correlation between SP and elevation, we estimated the gradient of the SP per unit topographic elevation to be about -1.4 mV/m. In general the gradient varies depending on geology, it is usually -1 mV/m to -10 mV/m in Japan (ISHIDO, 1989). The value of -1.4 mV/m is reasonable considering of the low resistivity in the surface layer of Shinmoe-Dake. We assumed the topographic SP gradient to be constant throughout the target area and obtained a corrected SP map as shown in Fig.3. The intensity of the positive patches at the fumaroles in the crater basin became as weak as 10 mV after the topographic correction. On the other hand, the negative anomaly below the crater lake was pronouced. Consequently, the positive patches became negligible compared to the negative anomaly in the crater lake. This result is natural if we again take the low resistivity and the weakness of the fumarolic activity into consideration. The positive anomalies on the eastern and southern slopes also became dominant after subtracting topographic effects.

4. Negative Anomaly below the Crater Lake

Most previous studies of self-potential in volcanic areas have reported positive SP anomalies in thermal zones, active fissures or craters (e.g., ZABLOCKI, 1976; BALLESTRACCI,1982; MASSENET and PHAM, 1985; NISHIDA and TOMIYA, 1987; HASHIMOTO and TANAKA, 1995). However, as we can see in Fig.3, the spatial distribution of SP on Shinmoe-Dake shows a negative anomaly in the crater. The negative anomaly amounts to -150 mV with a diameter of about 500 m. In Shinmoe-Dake's case we propose that drainage of water at the bottom of the crater lake causes the streaming potential. The streaming potential is an electrokinetic phenomenon, which originates in the electrical double layer at the interface between solid and liquid. This potential is generated by selective transport of ions along the fluid flow through a porous medium. Positive charges tend to be transported along the flow under the condition of typical crustal rock-water system. If water seeps from the crater lake of Shinmoe-Dake, some streaming potential accompanying the downflow should be generated. This streaming potential will cause a negative SP anomaly on the ground (or lake) surface. In the following discussion we will quantitatively examine whether the electrokinetic process is a dominant cause of the present negative anomaly or

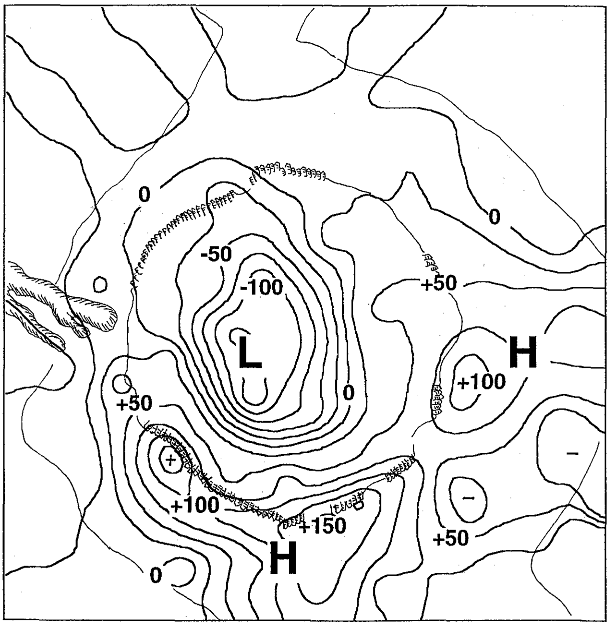

Fig. 3. Self-potential map (after topographic correction) in the same area as Fig. 1. Units of SP values and contour intervals are the same as in Fig. 2.

not. The possibilities of other mechanisms will be discussed in a later section.

Drainage of water from the crater lake can be dealt with as an example of source free flow across a boundary with different electrokinetic coupling coefficients. According to the capillary model (ISHIDO and MIZUTANI, 1981) for a porous medium, total electric current by electrokinetic coupling, ***I***, can be expressed as;

$$I = \left.\frac{\eta t^{-2}\varepsilon\zeta}{k}\right|_1^2 \cdot jA, \tag{1}$$

where the symbol $|_1^2$ indicates the change in the physical parameters on the left from medium 1 to medium 2 accross the boundary. η, t and k denote porosity, tortuosity and permeability of the medium, respectively. ε is the dielectric constant of the permeating fluid. ζ is the zeta potential of the electrical double layer. j denotes fluid flow per unit area. A is the cross-section across which fluid flows (in this case, the crater lake area). Let us assume $\eta t^{-2}=0.1$ and $\zeta=1\times10^{-2}$ V as realistic values, They are typical ones in laboratory experiments (ISHIDO and MIZUTANI, 1981). ε is taken as 7×10^{-10} F/m for water at 27 °C. A is given as 5×10^{4} m^2. We must know j and k in order to estimate I.

We can estimate j, water drainage, from the crater lake water balance. Variation of the water volume in a closed lake, ΔV, is expressed as;

$$\Delta V = (Qin-Qout)\cdot\Delta t - E\cdot\Delta t\cdot A + P\cdot A, \tag{2}$$

where Qin : surface and subsurface water infiow from the surroundings (m^3/sec), $Qout$: seepage from the lake (m^3/sec), Δt : lapse of time (sec), E : evaporation (m/

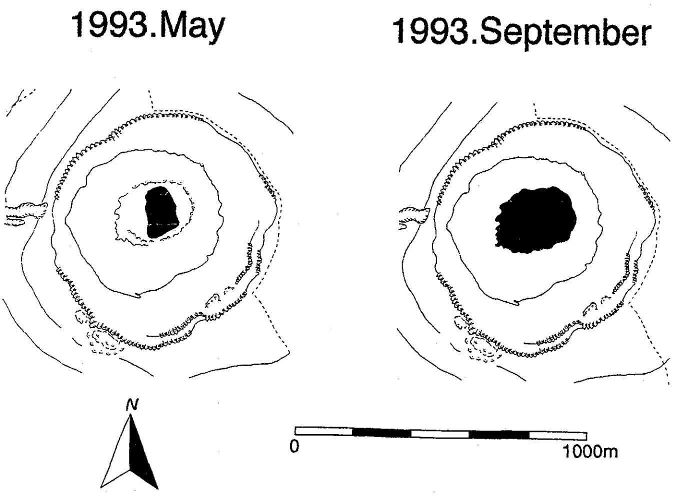

Fig. 4. Snapshots of the crater lake of Shinmoe-Dake in May 1993 (Left) and in September 1993 (Right). The crater lake is indicated with black color. The precipitation amounted to 7000mm from May to September in 1993, which was unusually high. The crater lake water level increased by about 15m during that period.

sec), $\boldsymbol{P}$: precipitation (m) during time Δt. In this study we deal with the period from May to September of 1993, during which we had unusual precipitation (about 7000 mm in five months) and consequently the water level of the crater lake increased by about 15 m (see Fig. 4). Δt is taken as 3×10^{8} sec. ΔV is estimated as 4×10^{5} m^{3}. We assume that $\boldsymbol{E}$ is 50 mm/month, which is a typical evaporation rate in Japan, since we have no evaporation data on Shinmoe-Dake. $\boldsymbol{A}$, the lake area, is given as 5×10^{4} m^{2}. Consequently, we obtain the evaporation and the precipitaion terms as $E\cdot\Delta t\cdot A=1\times10^{4}$ m^{3} and $P\cdot A=4\times10^{5}$ m^{3}, respectively. As for Qin, we have poor knowledge. In this study we take half of the precipitation inside the rim of the crater as Qin. Therefore we obtain $Qin\cdot\Delta t=1\times10^{6}$ m^{3}. Comparing the terms in eq.(2) we can neglect the evaporation term. Accordingly, we obtain $Qout \fallingdotseq Qin \sim 8\times10^{-2}$ m^{3}/sec and we have $j=Qout/A=2\times10^{-6}$ m/sec.

Permeability $\boldsymbol{k}$ of the ground can be estimated from Darcy's law,

$$j=\frac{k}{\mu}\cdot\nabla P, \qquad (3)$$

where ∇P is the pressure gradient. In this study we are discussing the conditions around the boundary between the lake and the ground. Therefore we regard ∇P as hydrostatic pressure at the bottom of the crater lake, *i.e.* 1.5×10^{5} Pa. μ is taken as 1×10^{-3} Pa•s, which is the viscosity of water at 25°C. From eq. (3), we obtain $k=1\times10^{-14}$ m$^{2}=1\times10^{-2}$ darcy.

Finally, substituting the values estimated above for $\boldsymbol{j}$ and $\boldsymbol{k}$ in eq. (1), we can determine the total electric current $\boldsymbol{I}$ as 6 A.

Let us examine the plausibility of the estimated value of $\boldsymbol{I}$. We can calculate

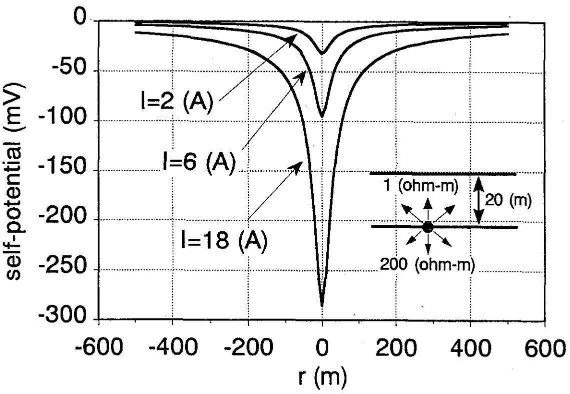

Fig. 5. Calculated SP profiles (cross section including the current source) for a two-layer model with a single point source at the boundary between the upper (lake water) and the lower layer (ground). The resistivities of water and soil are fixed at 1 and 200 ohm-m, respectively. The upper layer thickness, i.e. the lake depth, is fixed at 20m. The cases I = 2, 6, and 18 A were calculated.

what the SP profile on the ground (or lake) surface should be for a current source at a specified point. Negative electric current sources appear at a boundary of electrokinetic coefficients. In this case the lake bottom acts as the boundary. Hence, we should consider a disk-like current source at the lake bottom. As the first-order approximation, we assume a single point source of electric current placed at the boundary between lake water and ground. We calculate the two layered (lake water and ground) case. See Fig. 5. We assume that the resistivity of the upper layer (water) is 1 Ω-m because Shinmoe-Dake lake water is supposed to contain ions to some extent so that its resistivity should be lower than that of meteoric water. The thickness of the upper layer is 20 m (lake depth). According to the magnetotelluric measurements by KAGIYAMA (1994b), the resistivity of the lower layer (ground) is 200 Ω-m. We calculated SP profiles on the lake surface in the cases $I=2$ A, 6 A and 18 A. The profile with the current source of 6 A is almost the same as the observation in its intensity and lateral expansion. Accordingly, the electrokinetic process can well explain the negative SP anomaly in the summit crater.

5. Positive Anomalies on the Eastern and Southern Slopes

Let us consider the cause of positive anomalies on the eastern and southern slopes. Thermoelectric and electrokinetic effects can generate a positive SP anomaly. According to ground resistivity measurements by the magnetotelluric method by KAGIYAMA (1994b), low resistivity zones (< 3 Ω-m measured in the ELF band) are roughly coincident with positive SP anomalies. This correspondence suggests upflow of water heated beneath the area. Ground temperature data should be a definite clue for such an interpretation. We should pursue temperature measurements in the future.

Electrochemical effects, or chemical concentration cells, can also generate a positive SP anomaly. As will be discussed in a later section, anomalies through this mechanism are not expected to exceed several tens of millivolts. Therefore, it is difficult to attribute the positive anomalies to electrochemical effects only. However, we should also take account of the lateral inhomogeneity of deposits of Shinmoe-Dake. IMURA and KOBAYASHI (1991) made isopach maps of the pyroclastics, pumice fall and ash fall deposits of some recent eruptions of Shinmoe-dake. These deposits have eccentric distributions with principal directions to the east or the east-southeast. Such concentration of deposits can generate an anomaly in self-potentials, though we still have not identified such materials acting as a chemical concentration cell.

6. Discussion

Besides the electrokinetic effects, there are several possible mechanisms which cause a negative SP anomaly on the ground surface. We will briefly examine their plausibility as couses of SP anomalies on this volcano.

Electrochemical effects

Chemical concentration cells may generate electric potentials. However, the potential by this mechanism does not exceed several tens of millivolts (CORWIN and HOOVER, 1979) in the ordinary geothermal area except in the special cases such as an alunite field (GAY, 1967). It does not seem that the negative anomaly of Shinmoe-Dake is caused by the electrochemical process.

Redox reaction effects

Some kinds of conductive mineral deposits are known to generate negative self-potential anomalies. SATO and MOONEY (1960) proposed a mechanism by an oxdation-reduction reaction. A conductive mineral deposit serves as a path for electrons from the reducing environment at depth to the oxidizing one in the superficial layers. Resistivity measurements by the magnetotelluric method with VLF and ELF radio waves (KAGIYAMA, 1994b) do not show any indication of such a conductive mineral deposit beneath the crater of Shinmoe-Dake. Therefore this mechanism cannot be a major cause for the SP anomaly in this case.

Thermoelectric effects

If there is a temperature gradient across a sample of rock, then a corresponding voltage gradient will appear. NOURBEHECHT (1963) presented thermoelectric coupling coefficients for a variety of rocks and gave the spherical source model. According to his model calculations, the thermoelectric process can generate either positive or negative anomaly. However, we must assume an unrealistically large temperature contrast between inside and outside a spherical source (~1000°C) in order to explain the anomaly of Shinmoe-Dake, hence we can safely rule out this possiblility.

Now we conclude that the negative SP anomaly in the summit crater can be explained only by the electrokinetic effect.

7. Summary and Conclusions

Several SP anomalies were found on Shinmoe-Dake, one of the active volcanoes in the Kirishima volcanic group. The major features are the concentric circular negative anomaly in the crater basin and the positive anomalies in the eastern and southern slopes. The streaming potential by drainage of water from the crater lake is the most plausible cause for the negative anomaly. The cause of the positive anomalies on the eastern and southern slopes is not certain, though streaming potentials by subsurface hydrothermal upflows or electro-chemical effects with concentration of deposits may be possible candidates.

Positive patches exist in the raw SP map around fumaroles in the crater basin. They can be mostly ascribed to topographic effects, and hence, the streaming potential by fumaroles is concluded to be negligibly small in the target area.

Acknowledgments

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霧島火山群・新燃岳の自然電位測定

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霧島火山群に属する成層火山新燃岳において，火口を含む約1km四方の自然電位分布を調査した．新燃岳火口底の自然電位は，過去に調べられたいくつかの活火山の例に反して負の異常を示すことがわかった．この負異常の原因についていくつかの可能性を定量的に検証した結果，火口湖からの漏水に伴う流動電位がその主要な原因であるとの結論を得た．

山体東斜面と南斜面には正の電位異常が見られる．MT法による比抵抗測定によって得られている低比抵抗層の分布と，この正の電位異常の分布は良い一致を示すことから，地下での熱水の上昇が示唆される．しかしながら，地中温度のデータがないためこれは確証的ではない．

地形効果補正前の分布図では，火口内の噴気に伴って正の電位異常があるように見えるが，これは見かけ上のものであり，地形効果を除去すればこの正の異常は，火口底の負異常に比べて無視できるほど弱小なものであることがわかった．これらのことから考えて，現在のところ新燃岳の火口直下の熱水活動はさほど活発ではないといえる．