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Self-Potential Studies in Volcanic Areas (5) — Rishiri, Kusatsu-Shirane, and White Island —

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Abstract

We performed SP profiling or mapping in three volcanic fields, Rishiri (northern Hokkaido), Kusatsu-Shirane (central Honshu) and White Island (northern New Zealand). The SP profile on the western flank of Rishiri volcano showed a remarkable high in the summit side, which is similar to many other active volcanoes. Assuming a negative ζ-potential, it is likely that Rishiri volcano has a large hydrothermal circulation system, and therefore, still has enough thermal energy to maintain this circulation. Kusatsu-Shirane volcano inversely showed a decreasing trend toward the summit. It is a contradictive result to the previous knowledge that a volcano with remarkable hydrothermal system shows negative SP on the top. We suspect that the low pH of ground water in this area makes ζ-potential null or positive, resulting in the reversed surface SP profile to ordinary cases. This idea should be examined by laboratory experiments in the future. In the Main Crater of White Island volcano, we found some small-scale anomalous patches associated with fumaroles and steaming ground. The small variability of SP is probably attributed to the very low resistivity of the ground.

1. Introduction

Remarkable self-potential (SP) anomalies exceeding 1 V are found in some volcanic areas. Such large potential differences on the ground have been an object of research interest since the first attempts of measurement on Vesuvius by Palmieri (1894). In Japan, there was a series of studies on the vertical SP in some volcanoes in the Aso area by Namba (1938), in which he reported upward earth-current on volcanic flanks and discussed the relationship with the streaming potential. In the 1950s, SP was widely utilized as an inexpensive exploration tool for conductive ore bodies, whose theoretical basis is the electrochemical reactions (Sato and Mooney, 1960). This kind of application, however, became unpopular after the 1960s. Nourbehecht (1963) formulated the SP generation and applied his theory to some source mechanisms including the electro-kinetic phenomena (EKP) (or streaming potential). After the successful application to Kilauea, Hawaii by Zablocki (1976), which showed a clear correspondence between volcanic activity and SP anomaly, many researchers have attempted to apply this method to volcanic and geothermal fields. Many of them reported positive SP anomalies and their time variations corresponding to active craters or fissures, attributing such anomalies to EKP associated with subsurface hydrothermal flow (e.g. Hashimoto and Tanaka, 1995 ; Nishida et al., 1996 ; Zlotnicki et al., 1998 ; Kanda and Mori., 2002). The EKP is considered to be a major mechanism of SP generation in active volcanic areas because thermally-driven subsurface fluid flow is common to such fields. However, other generation mechanisms should also be accessed carefully in some cases with small-scale anomalies of the order of 10 to 100 mV. Even with the EKP, there are still several unsolved problems, especially in the context of application to actual fields. Unfortunately, the SP is not yet such a well-established exploration technique as active electric soundings or magnetotellurics but, to some extent still an object to be investigated.

The main body of this paper reports the results and preliminary interpretations from recent surveys in three volcanic areas. Prior to presenting the results, we review recent development in this research field and summarize the relevant problems.

2. Recent problems in the research field of self-potential

2.1 ζ-potential

Fundamental experiments of the ζ-potential in rock-water system were performed by Ishido and Mizutani (1981). They revealed that ζ-potential was strongly affected by pH, ranging from about -0.1 V to almost zero as pH varies from 12 to 2. They also investigated the temperature dependence of ζ-potential from 20 up to 80°C, indicating increasing magnitude (polarity was negative) with temperature. Since SiO_2, generally taking a negative value, is the commonest component to most rocks, ζ-potential in most rock-water systems had widely been believed to take negative values at least under moderate pH condition. Recent experiments by Hase et al. (2003), however, showed it was not always the case. They used natural rock samples with various chemical components from Aso volcano and found that some of them had positive ζ-potential even in moderate pH conditions. Their result suggests that ignorance of the polarity of ζ-potential may cause critical misinterpretation of field SP data. They also investigated the relationship between ζ-potential and contents of major elements in the rock samples to verify that bulk ζ-potential is roughly determined by the ratio of the consisting elements. Their experiments, focusing on the conditions of solid phase at liquid/solid interface, were performed at a fixed temperature (30°C) and with KCl solution. Further experiments with more realistic conditions are necessary in the future from the viewpoint of application to field data.

2.2 EKP in two-phase flow

Although it is known that flow of superheated (or dry) steam does not produce the streaming potential (Tyran and Marsden, 1985), the EKP by liquid/vapor two-phase flow is not well understood. Generally in two-phase flow in porous media, the liquid phase tends to cover the solid surface and the vapor phase mostly exists in the middle of the pore space. Transport of electric charges (or drag current) by the EKP hence does not decrease significantly even if the liquid saturation ratio decreases, resulting in the larger streaming potential per unit mass of fluid flow (Morgan et al., 1989). Morgan et al. (1989) also pointed out the significance of the decrease of bulk electrical conductivity by increasing vapor saturation ratio. This effect makes the streaming potential coupling coefficient larger, since the same amount of drag current produces larger voltage difference in less conductive media. We would like here to put an emphasis on the effect of non-uniformity in two phase flow, namely, in which the liquid and vapor phases have different flow velocities. Considering a vertical two-phase flow, for instance, a "heat pipe", in which vapor-liquid counterflow exists under a certain condition (Eastman, 1968). In such a case, the downward flow of liquid phase, being responsible for the drag current, may cause a negative SP anomaly on the ground surface. This implies that not all the fumarolic or steaming fields should be accompanied by positive SP anomalies. The condition of such counterflow might depend on flow velocity, liquid saturation ratio, and so on. Further laboratory and field experimental studies are necessary to delineate the EKP in actual geothermal or volcanic fields.

2.3 numerical modeling

Modeling of fluid flow in porous media, in combination with heat transfer and subsequent generations of electric current and field, is essentially important to infer the subsurface flow from surface SP measurements. Some sophisticated numerical simulators (e.g. Ishido and Pritchett, 1999), which can treat various physical and chemical parameters have been developed in recent years. Such simulators will be useful for problems such as ; the effects of permeability and resistivity structures on SP generation and related topographic effect, the SP generations in two-phase or unsaturated zone, and the evolution of hydrothermal system associated with a thermal intrusion.

3. Results of SP surveys and preliminary interpretations

This paper reports the results of SP surveys from Rishiri (northern Japan), Kusatsu-Shirane (central Japan) and White Island (northern New Zealand) volcanoes. Although these results are for the moment only preliminary because of the limitations of measurement coverage, they allow us to point out some characteristic features to each field which contain important problems of SP generation in volcanic areas. For all the surveys we measured SP by "the total field method" in which a reference electrode was fixed at a certain point and a potential electrode was shifted from the reference point up to some 500 m distance away, depending on the situation, measuring at 50 m spacing. After completing the first roll of 500 m cable, we rewound it back to the reference to check the electrode drift. Then, shifting the reference to the first end, we proceeded to another sequence of profiling. At each measuring site, we scraped off the surface soil or vegetation to make three neighboring dimples to put the electrode in. This process is generally important to keep a good contact between the electrode and the ground and to avoid very local scale SP anomalies. We took an average of the measurements at the three dimples as the representative value of the site. We used Cu-$CuSO_4$ and Pb-$PbCl_2$ non-polarized electrodes. A handy GPS (eTrex by Garmin Inc.) was used for positioning of the measuring sites.

3.1 Rishiri volcano

Rishiri is a Quaternary volcano island of 18×16 km which is located in northern Hokkaido, Japan. It consists of alkaline basalt and calc-alkaline andesite to dacite rocks (Katsui, 1953; Kobayashi, 1989). Ishizuka (1999) clarified the petrological evolution of Rishiri volcano showing that the volcano commenced its formation from c.a. 200 ka and reached to the peak of eruption rate at c.a. 40 ka. He inferred that the volcanic history of Rishiri can be characterized by an isolated diapirism and by its cooling process. From this point of view, he concluded that volcanic life time of Rishiri volcano has almost expired. There is no historical record of eruptions at Rishiri volcano. However, it is classified as an active volcano by the new category defined by Japan Meteorological Agency since 2003 because it has some geological evidences of volcanic activities younger than 10 ka.

No SP surveys have ever been carried out at Rishiri volcano before this study. We may address research targets in this field from two different perspectives. One is a comparative approach to other volcanoes in terms of the relationship between volcanic history and SP anomalies (polarity, intensity or size scale). The other is to investigate the relationship between SP anomalies and the ζ-potential variations of volcanic rocks in Rishiri, which shows a wide range of chemical content from basalt to rhyolite. However, as a first step in this study, we addressed our main target in clarifying whether Rishiri had a large-scale SP anomaly that covers the whole volcanic edifice. Kutsugata trekking route in the western part of the island was chosen for this purpose. We conducted our SP profiling along the path between 400 to 1400 m (ASL) in altitude (corresponding to the 3rd to 9th station) from 10 to 13 of August, 2003. We could not pursue the survey above the 9th station because of the danger due to steep topography.

Figure 1 shows the survey route. This route is mostly covered with the middle stage volcanics (MSV; after the definition by Ishizuka, 1999) which comprises andesite to dacite lava forming the central part of the volcanic edifice. Profiled SP along the route and corresponding topography are shown in Fig. 2. The SP above 1,100 m (ASL) is noticeably high, showing the potential of +700 ~800 mV compared to the reference point situated at the 3rd station (400 m). Besides this main feature, another positive SP zone is recognized between the altitude of 600~900 m (ASL), which indicates c.a. 300 mV higher than its proximity. The overall profile clearly indicates the higher SP towards the summit which is similar to many results from other active volcanoes.

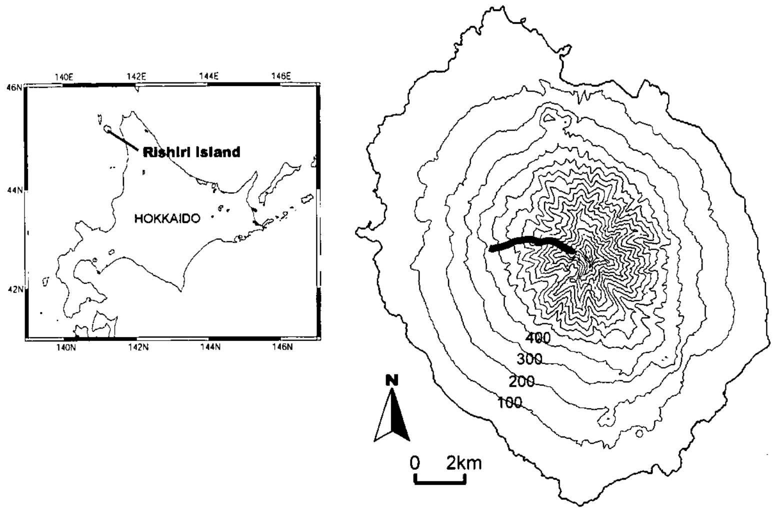

Fig. 1. Location map of Rishiri island. The survey line is shown together with topographic contours of the island at 100 m intervals.

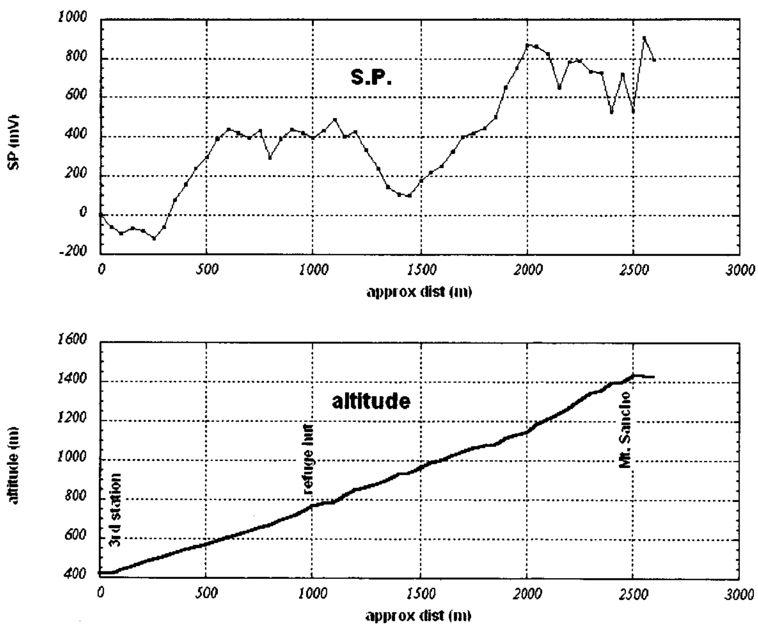

Fig. 2. Self-potential (upper panel) and topography (lower panel) along the survey line in Fig. 1. The horizontal axis indicates the approximate distance along the route.

The observed anomaly is larger than normal values due to thermoelectric or electrochemical effects, and hence, can be attributed to EKP. Since the central part of Rishiri volcano is mostly comprised of andesite to dacite deposits with moderate to high SiO_2 content (Ishizuka, 1999), it is likely that ζ-potential in this area takes negative value. Thus, according to an ordinary EKP model with a negative ζ-potential, a large-scale hydrothermal circulation with an upward flow beneath the summit is suggested from the observed SP profile. In other words, it is suggested that Rishiri volcano still has enough thermal energy to maintain such a hydrothermal circulation within its edifice. However, there is the possibility that the ζ-potential is positive as reported in the laboratory experiments of Aso's volcanic rocks by Hase et al. (2003). If this was the case, we could have a normal downward circulation of rainwater. Since we do no at present have any ζ-potential measurements using samples from Rishiri, we cannot completely exclude the possibility of the latter case. Since we do not at present have any ζ-potential measurements using the samples from Rishiri, we cannot completely exclude the possibility of the latter case.

The survey line of this study is limited in the upper half of the island. Measurements should be extended to the lower half in the future to verify whether the SP continues to decrease toward the western coast resulting in the very large positive anomaly at the summit, or rebounds toward the coast showing a typical "W-shaped" feature as in many active volcanoes. We should also be careful of the variation of ζ-potential, since the lower part of the western Rishiri is covered with alkaline basalt lava flows which is obviously different from the deposits in the central part.

3.2 Kusatsu-Shirane volcano

Kusatsu-Shirane is a Quaternary andesitic to dacitic volcano situated near the boundary between Gunma and Nagano prefectures, central Japan (Uto et al., 1983) (Fig. 3). At least fourteen eruptions can be seen in historical records since 1805. Although the volcanic activity in historical time is limited to phreatic explosions from Yugama crater and vicinities, fumaroles around the volcano are still active and a subsurface hydrothermal system is inferred to provide heat and fluid to the flanking hot springs (Ossaka et al., 1998). Yugama crater, the main active center of recent years, has an acidic lake to which several tones of hydrothermal fluid per day is supplied from subsurface (Ohba et al., 1994). A previous SP survey around the Shirane pyroclastic cone, the summit of the volcano, in 1994 is reported in Yamazaki et al. (1997). According to their result,

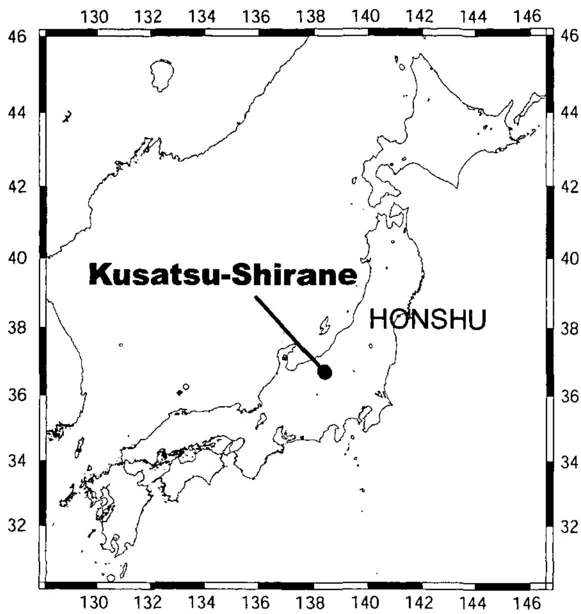

Fig. 3. Location map of Kusatsu-Shirane volcano.

the SP of this area is relatively flat and no distinct SP anomalies were detected around the Yugama crater. They attributed the absence of distinct SP anomalies to the low electrical resistivity of the ground (Katsura et al., 1996).

In this study, we measured an SP profile from the SW part of the Yugama crater toward Kusatsu spa in the ESE direction along a walking trail. In contrast to the target area in Yamazaki et al. (1997), which concentrated on the summit area (about 2×2 km), our survey provides a longer (8 km in total) SP profile, in which we initially expected there would be a broad SP anomaly, more positive toward the summit. The survey route and some major landmarks are overlaid on the geological map by Uto et al. (1983) in Fig. 4. One end of this route is at the SW of Yugama crater and the other is located near Bandai-ko, one of the hot-spring sources of Kusatsu spa. Along the route, pyroclastic cones of Shirane (S), Ainomine (A), Moto-Shirane (M) and some units of lava flow such as Aoba (Ab) and Sessho (Ss) lavas are intersected. Major hydrothermal activities along the route can be seen at Yugama crater, Sessho fumarolic zone and Bandai-ko spring. The survey was conducted on September 17~19, 2003.

The profiled SP and corresponding topography are shown in Fig. 5. Features of the SP profile are summarized as follows. (1) Neither Yugama crater

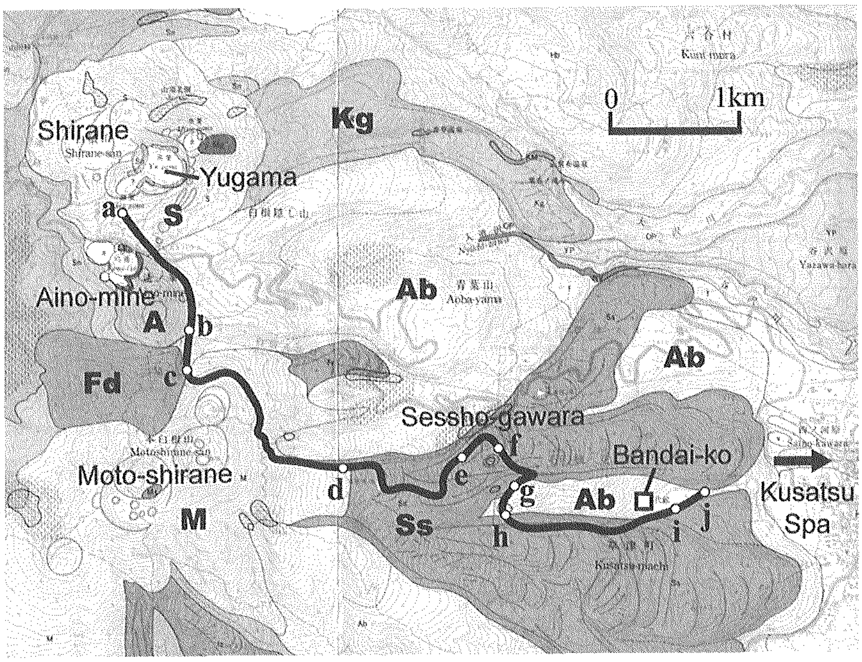

Fig. 4. SP survey route (thick black line) shown on the geological map by Uto et al. (1983). Symbols for geological units are after Uto et al. (1983); S (Shirane pyroclastic cone), A (Aino-mine pyroclastic cone), M (Moto-Shirane pyroclastic cone), Fd (Futagoyama lava dome), Kg (Kagusa lava), Ab (Aoba lava) and Ss (Sessho lava). Lower-case characters with open circles indicate some geological boundaries, corresponding to the ones in the upper panel of Fig. 5.

(around **a** in Fig. 5) nor Sessho-gawara fumarolic zone (**e**~**f** in Fig. 5) was electrically high. The latter even shows relatively low potential compared to its proximity. (2) The overall profile indicated higher potential toward the lowland. Focusing on the trends, the SP was almost flat between the summit area and Sessho-gawara, while it tended to increase in the lower part toward Bandai-ko. The maximum reached +700 mV referred to the summit end. The SP tended to decrease again in the area below Bandai-ko. (3) Several SP anomalies of smaller scale (some hundred meters in horizontal scale) seem to be superposed on the overall trend. Some of them apparently correspond to the surface geology. For instance, we found some hollows of 100~300 mV corresponding to the intersections of Aoba lava (**b**-**c**, **g**-**h** and **i**-**j** in Fig. 5). Another example is a local SP maximum at the boundary of Moto-Shirane pyroclastic cone (M) and Sessho lava (Ss) (corresponding to **d** in Fig. 5).

The absence of distinct SP anomaly in the summit area is similar to the

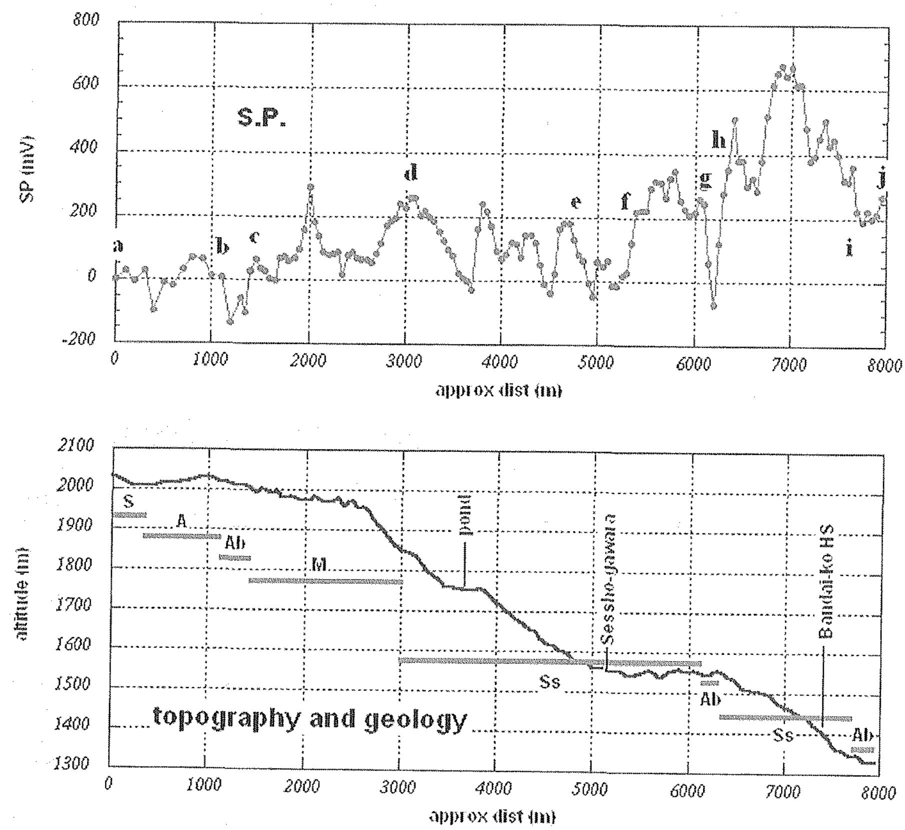

Fig. 5. SP (upper panel) and topography (lower panel) profiles along the survey route. The horizontal axes indicate the approximate distance along the route in meters. The lower-case characters in the upper panel correspond to geological boundaries shown in Fig. 4. Symbols with horizontal bars indicate surface geology (See the captions of Fig. 4).

results of Yamazaki et al. (1997). However, it is now unlikely that an attenuated high SP in the summit area exists that is being obscured by the low ground resistivity, since a decreasing trend toward the summit is obvious in our longer profile. As an alternative explanation, we propose a possibility of positive ζ-potential in this area. There are some geochemical implications which support this idea. For instance, lake water of Yugama crater (pH$=$1.1 ; Ohba et al., 1994) and hot spring water of eastern flank (Yubatake and Bandai-ko) (pH$=$1$\sim$2 ; Ossaka et al., 1998) show low pH, which may contribute to change the ζ-potential from negative to positive (Hase et al., 2003). Concentration of Al^{3+} in the hot spring water of Kusatsu spa amounts to about 50$\sim$250 ppm (Ossaka et al., 1998), corresponding to an order of 10^{-3} mol/l , which effectively moves the ζ-potential from negative to positive (Ishido and Mizutani, 1981). Considering such effects, it is likely that ζ-potential of Kusatsu-Shirane volcano takes null to positive values in terms of large-scale fluid circulation. One of the possible explanations for the difference in the trend of SP profile bounded at Sessho-gawara fumarolic zone is the injection of volcanic gas into the ground water from higher altitude, which results in the chemical composition of the pore water and consequent variation of ζ-potential. It is necessary in the future to pursue laboratory measurements of ζ-potential under realistic physical and chemical conditions in this area to verify the possibilities described above.

It is difficult to identify the generation mechanism for each of the small short wavelength SP anomalies. However, as pointed out above, some of them clearly correspond to particular units of surface geology. Variability in the electrical resistivity and/or hydrological permeability can affect the streaming potential coefficient. Electrochemical effects are also the possibility. As is shown in the geological map, Kusatsu-Shirane volcano consists of several layers of lava flows and pyroclastic deposits in a complex form. Such complexity and inhomogeneity prevent us from a simple interpretation of SP mapping. In such an area small-scale SP anomalies are not very informative.

There are several possible models for the negative SP in the Sessho-gawara fumarolic zone. As for EKP, we have two options. The first one is the EKP with positive ζ-potential associated with upward fluid flow. The second is the EKP with negative ζ-potential associated with gas/liquid two phase flow (gas phase fumes up, while liquid phase condenses down). In either case, ζ-potential measurement in a realistic environment is a key to understand the process occurring here. We consider that ζ-potential of sulfide materials should also be taken into consideration in such field. Beside the EKP, we should also examine the possibility of electrochemical effects (redox potential; Sato and Mooney, 1960).

3.3 White Island (New Zealand)

White Island is an andesitic to dacitic volcano located off the northeastern shore of the North Island of New Zealand (Fig. 6). The most distinct topographic feature of this volcano is the horseshoe-shaped Main Crater of approximately 0.5×1.3 km elongated in NW-SE direction. This Main Crater is composed of multiple craterlets and has had a crater lake at its NW end (the central part of the island) since 1993. Fumarolic activity with sulfur deposition and

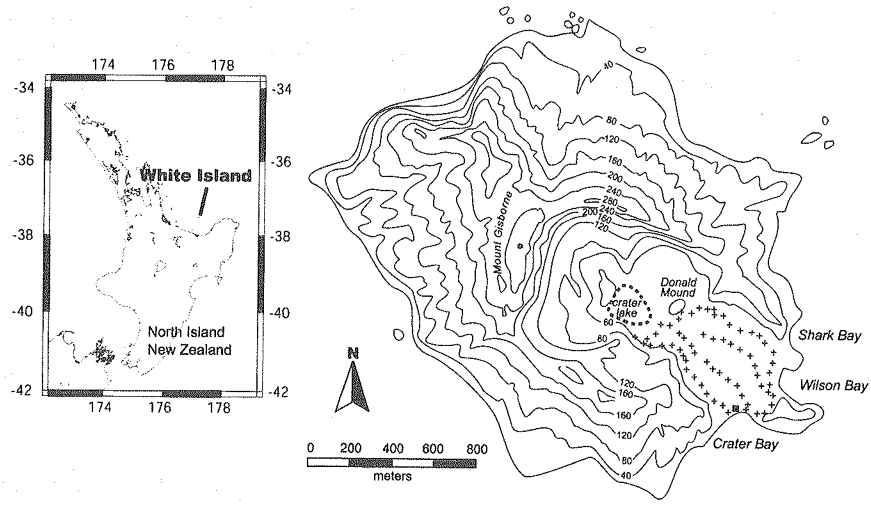

Fig. 6. Location map and topography of White Island. Cross (+) symbols indicate the measurement points of SP. A solid square indicate the voltage reference.

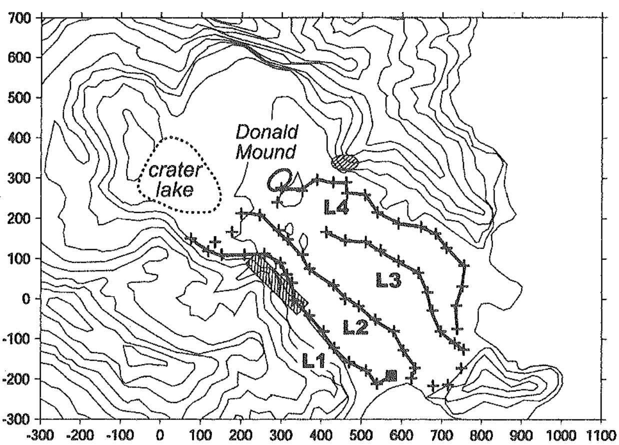

Fig. 7. A detailed map of the survey area. Cross (+) symbols indicate the measurement points of SP. A solid square indicate the voltage reference. Topographic contours are drawn at 20 m intervals. The grid unit is in meters.

steaming ground can be seen at some places on and around the crater floor margins. The volcano has small eruptions every few years. Recent major eruption sequences occurred in 1976-1982 and 1986-1994. The Geological Survey of Japan and the Institute of Geological & Nuclear Sciences Ltd (NZ) had a joint research program and the conducted SP surveys in 1993 and 1996, as

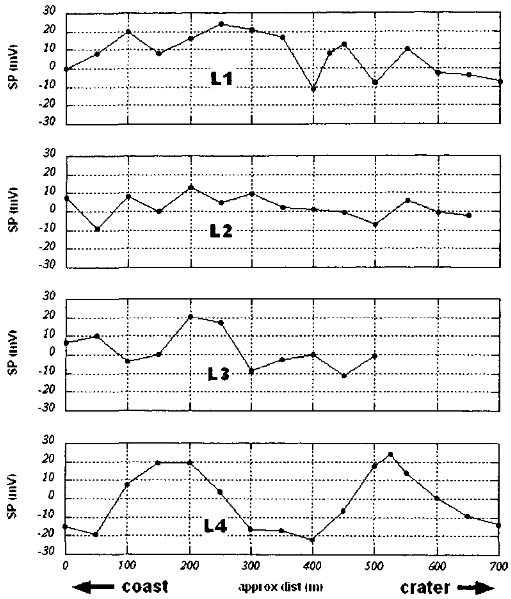

Fig. 8. SP profiles along the lines L1 to L4 shown in Fig. 7. The horizontal axes indicate the approximate distance along the route in meters. Note that the coast and crater sides are on the left and the right, respectively.

well as audio-frequency magneto-telluric (AMT) survey in 1996 (Nishi et al., 1996). Our SP survey was performed on December 12, 2003 as part of a joint research program by Japanese university group and IGNS. During the seven years after the previous survey by Nishi et al. (1996), White Island has experienced several months of ash emission in mid-2000, and in the last ten years or so there has been a remarkable increase of water level in the crater lake.

Our survey covers the majority of the Main Crater floor except for the northernmost corner and lake area as shown in Fig. 6 and 7. For practical reasons, we placed the reference electrode near the coast of Crater Bay (shown as a solid square in Fig. 7) and deployed SP measurements along four lines (L1 ~L4), which were roughly parallel to the major axis of the Main Crater and at several additional points. The lines L1 and L4, following the NE and SW margins of crater floor, passed by fumaroles with steaming ground (the hatched areas in Fig. 7). Self-potential profiles for each survey line and a compilation of all the measurements plotted as a contour map are shown in Fig. 8 and 9, respectively. Generally speaking, potential variability of this area was small, ranges within approximately $-20 \sim +20$ mV. This feature is similar to the

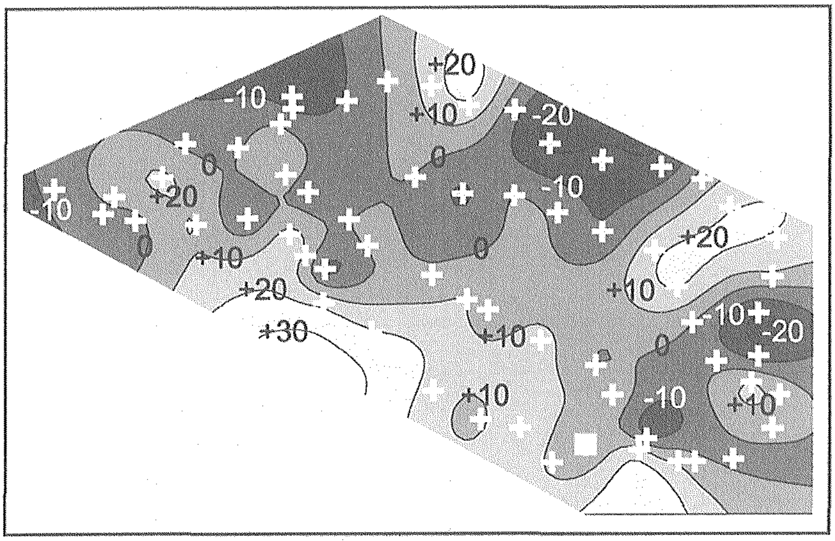

Fig. 9. A Contour map of SP on the Main Crater floor of White Island. Contour interval is 10 mV.

results from Nishi et al. (1996). Taking a closer look at the L1 and L4, we can recognize positive SP anomalies of about +20 mV corresponding to the fumaroles and steaming ground. The high SP value on the L1 can also be found in Nishi et al. (1996)'s result in 1996.

Although the Main Crater floor is slightly inclined upwards to the NW direction (c.a. 10 m/500 m), it has little undulation and almost homogeneous surface geology. Therefore, it is likely that the EKP due to subsurface fluid flow and fumarolic activity are responsible for the SP anomalies in this area. The EKP is particularly indicated because the positive SP patches accompany non-superheated fumaroles at the crater margins. However, the overall variability of SP in this area is small compared to the ones reported in other volcanoes. One reason for the low values is probably the very low resistivity of the ground (a few Ωm or smaller in apparent resistivity of AMT band ; Nishi et al., 1996). In other words, even though an EKP due to subsurface fluid circulation does exist, the surface SP is attenuated and masked by the very low resistivity of the ground.

We did not detect any distinct positive SP anomalies at the SE of the crater lake, which Nishi et al. (1996) reported in their 1996 survey having c.a. +30 mV. Similarly, we did not recognize noticeable negative SP patches in the middle of the crater floor, which they had in 1996. Instead, we found a positive zone in the middle-south area along the lines L3 and L4, which were not seen in 1996. Detailed comparison between the two mappings by us and Nishi et al. (1996) is difficult because of the location mismatch of measuring points. However, if the differences described above have significance, then a possible explanation is a change in the direction of ground water supply from/toward the crater lake due to the rise of the lake water level. There was probably a flow from the coast side towards the lake in 1996, which is likely to now be reversed with the much higher level of the lake.

4. Concluding remarks

Our SP profiling on the western flank of Rishiri volcano has revealed a large positive SP anomaly towards the summit, which is similar to many other active volcanoes. Assuming the negative ζ-potential in this field, it is likely that Rishiri volcano has an island-scale hydrothermal circulation system centered at the summit, and thus, still has enough thermal energy enough to maintain such a circulation. Kusatsu-Shirane volcano contradicted our initial expectation, indicating a decreasing SP trend toward the summit. It is a new finding that a volcano with a major hydrothermal system yielding considerable amount of hot spring water shows negative SP near its summit. We suspect that the low pH of ground water in this area makes ζ-potential null or positive resulting in the surface SP profile being reversed from normal. This idea should be examined by laboratory experiments in the future. In the Main Crater of White Island volcano, variations of SP are small but we found some small-scale anomalous patches associated with fumaroles and steaming ground. One of the possible explanations for the temporal change between two surveys in this study and in 1996 by Nishi et al. (1996) is a change in the direction of ground water supply from/toward the crater lake due to the rise of the lake water level. In this paper, we also pointed out some problems to be solved in the future such as laboratory experiments of ζ-potential and the EKP in two-phase flow and so on.

Acknowledgements

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