Self-Potential Changes and Subsurface Hydrothermal Activity Accompanying the 1990–1995 Eruption of Unzen Volcano

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The evolution of a hydrothermal system beneath the Unzen Volcano, one of the dacitic volcanoes in Shimabara peninsula, southwest Japan, was investigated by self-potential (SP) observations during the 1990–1995 eruption events. SP changes accompanying the eruption can be divided into three stages. In the first stage, March through June of 1991, the rapid growth of a distinct positive SP anomaly was detected by continuous observation in the vicinity of a lava dome which began extrusion in May 1991. The positive anomaly is thought to be caused by hydrothermal upflows induced around the intruded magma through electrokinetic coupling. In the second stage, July 1991 through December 1993, the lava dome erupted in an exogenous manner. The growth of a dipolar SP anomaly was detected by repeated surveys during this stage. The cause of this SP change is thought to be electrokinetic potentials associated with shallow hydrothermal circulation which grew at the west of the lava dome for over two years. In the third stage, from the beginning of 1994, the dome growth became endogenous. SP showed concentric increase around the dome. This SP change probably suggests the expansion of upflow zone at high temperature in shallow levels.

1. Introduction

Obvious self-potential (SP) anomalies have been observed in many active volcanic areas. In particular, positive SP anomalies, which are often associated with fumarole areas or thermal zones, are considered as a sign of subsurface hydrothermal activity. The most probable cause of these SP anomalies is thought to be the electrokinetic streaming potential produced by subsurface hydrothermal upflows; there is no promising candidate except the streaming potential which explains positive SP anomalies of several hundreds mV in magnitude. Zablocki (1976) detected positive SP anomalies corresponding to pit craters on Kilauea Volcano, Hawaii. Similar positive SP anomalies were also observed on Usu, Hokkaido Komagatake (Nishida and Tomiya, 1987), Soufrier (Zlotnicki et al., 1994a) and Piton de la Fournaise (Zlotnicki et al., 1994b) volcanoes. Recently, Ishido (1991) estimated the amount of subsurface hydrothermal fluid flow from equivalent electric current sources associated with SP anomalies observed on Izu-Oshima volcano. SP data was shown to be useful for developing a geohydrological model of the volcano.

A few previous studies have dealt with the temporal variation of SP in association with volcanic activity. Zablocki (1976) observed obvious temporal changes of a positive SP anomaly corresponding to a fissure eruption in Kilauea. Nishida and Tomiya (1987) and Matsushima et al. (1990) investigated the temporal SP changes on Usu volcano, Japan, and observed that a positive SP anomaly overlying the summit crater has decayed after the eruption in 1977. On Piton de la Fournaise volcano, a local but large SP anomaly (1500 mV, 150 m) along a dry fissure which was formed in the August 1992 eruption was found to disappear a few months after the eruption (Zlotnicki et al., 1994b).

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The eruption of Unzen volcano, started in November 1990 leaving 198 years’ dormancy, kept on its activity for more than four years, and almost subsided in May 1995. Total amount of the lava effusion was reported as about $2 \times 10^8$ m$^3$. This eruption event is quite suitable to investigate how subsurface hydrothermal circulation will be established when the magma abruptly intrudes into shallow levels after a long quiescent period. In order to monitor the expected rapid SP changes the author installed some continuous recording sites along the southwest direction from the active lava dome. In addition, he repeatedly made spatial SP surveys around the summit area including the dome to clarify the spatial size and extent of temporal changes. These observations started in March 1991 and almost covered the main part of the eruption period. Preliminary interpretations of the results in the early stages were reported in Hashimoto and Tanaka (1995). In this paper the author will present the updated results and propose a possible evolution process of subsurface hydrothermal circulation beneath Unzen volcano.


Unzen volcano, an active stratovolcano, which consists of a group of dacitic lava domes, is located at the center of Shimabara peninsula (32° 46' N, 130° 18' E) in Kyushu, southwest Japan.

![Location and topography of Unzen Volcano. Topographic ridges are emphasized by thick broken lines and valleys by thin broken lines. Height is represented in meters.](image)
The massif of the volcano extends approximately 20 km and 25 km in east-west and north-south directions, respectively including its skirts. As is shown in the topographic map of Fig. 1, the volcano has a horseshoe-shaped caldera open to southeast. Fugen-dake (Mt. Fugen), is situated in the central part of the caldera, while Myoken-dake, Kunimi-dake and Emaru-dake form a western part of the caldera rim. The southeastern part of the caldera rim is considered to have collapsed before the formation of Fugen-dake (Tanaka and Nakada, 1988). It has been revealed by geological studies that Unzen volcano has repeated lava dome extrusions with pyroclastic flows in every 4000 ~ 5000 years (e.g., Watanabe and Hoshizumi, 1995). The amount of products in the present summit eruption starting in 1990 is much larger than those of the last two flank eruptions which occurred in 1663 and 1792.

Major events during the eruption are summarized in the left column of Fig. 2. This eruption lasted unexpectedly long and the manner of the eruption can be characterized by different features

![Diagram](image)

**Fig. 2.** A time series showing the volcanic activity of Unzen. The meshed bars represent the period of activities of J (Jigoku-ato), K (Kujuku-shima) and B (Byobu-iwa) craters. Three stages of the self-potential changes are according to the description in Subsection 3.2. The effusion rates of lava are after Nakada and Shimizu (1995).
from period to period.

During November to December in 1989, a swarm of earthquakes, which preceded the eruption, occurred 15 ~ 20 km below Tachibana bay, approximately 10 km west of Fugen-dake. The hypocenters shallowed eastward to the west coast of Shimabara peninsula after July 1990 (Umakoshi et al., 1994). Volcanic tremors also started at this time (precursory seismic activity). On November 17, 1990, Fugen-dake started phreatic summit eruption at Jigoku-ato and Kujukushima craters leaving 198 years' dormancy. Then, Byobu-iwa crater started intensive ejection of dense volcanic ash on February 12, 1991 (fumarole and ash ejection activity). A lava dome appeared at the location of Jigoku-ato crater on May 20. Shallow earthquakes, severe ground deformations and some explosive events preceded the appearance of the dome. The dome, effusing and collapsing lava, gradually grew itself. The dome showed exogenous growth at early stages, which is characterized by repeated process of effusion and collapse of lava. However, endogenous growth, growing within by repeated injection into the dome body, accompanied by remarkable ground deformations became dominant after December 1993 (lava dome activity) (Kyushu univ. et al., 1994).

A temporal change of effusion rate is shown in the right panel of Fig. 2 (after Nakada and Shimizu (1995)). There were two pulses of magma supply; the first pulse took place from May 1991 to January 1993, and the second one from February 1993 to early 1995 (Nakada and Shimizu, 1995). Approximately ten thousand Merapi-type pyroclastic flows occurred since the appearance of the lava dome till the subsidence of the eruption in 1995 (Nakada and Shimizu, 1995). Effusion of lava almost stopped in early 1995 and the volcanic activity progressively receded thereafter.

3. Observations

3.1 Measuring systems

A research group including the author started SP observations in the summit area of Unzen volcano in March 1991, two months before the first extrusion of the lava dome. The site distribution of SP measurements is shown in Fig. 3. Stations for continuous observations are denoted by open circles with letters (A–G). Stations B, C, D, E and F were installed on March 20, 1991. Stations A and G were added on August 3, 1991 and on March 12, 1992, respectively. Although the survey area was free from the noise of AC power lines, the 22.2 kHz electromagnetic noise was severe because the VLF station for submarine communication is located in Miyazaki prefecture (about 150 km SSE of Unzen). Hence passive low-pass filters were inserted at each input of the data recorder placed at station B to avoid the aliasing. The voltage differences of C–B, D–B, E–B, F–B and G–B were lead to station B by electric cables and were recorded there on the data recorder in every 40 minutes. Repeated SP surveys were carried out approximately once a month at the sites denoted by solid circles in Fig. 3. Reliable data of the repeated surveys are available after December 1991.

Electrodes of the Pb-PbCl₂ type were used for both repeated surveys and continuous monitoring. An electrode used here consists of a lead wire and the powder of lead-chloride packed in a porous cup. The electrode is maintenance-free and suitable for a long-term observation since it consists of only solid materials (Electrodes using electrolytic solutions need periodic maintenance). The electrodes were wrapped with clay and buried at the depth of 0.3 ~ 0.5 m to minimize anomalous potential changes at the electrode-earth interface caused by rainfall. To check the stability of the electrodes, we sometimes measured the potential difference between the Pb-PbCl₂ electrodes (buried) and a Cu-CuSO₄ electrode (on the ground surface) at each site. The potentials of Pb-PbCl₂ electrodes referred to the Cu-CuSO₄ electrode were, in most cases, in the range of −450 mV ~ −500 mV.

In order to minimize the error of repeated measurements caused by very local SP around each site we buried these electrodes and made them fixed stations. The solid lines connecting
Fig. 3. Distribution of observation sites. Repeated survey points are denoted by solid circles, while continuous monitoring sites by open ones. Broken lines show the traces of extra-surveys which were also used in making the equipotential maps in Fig. 5.

each repeated site in Fig. 3 indicate single-wired electric cables along the measuring paths. We can cut the cable and measure SP at the site we need. This system made the field measurements easier and the data more reliable.

3.2 Results of self-potential observations

The 1990–1995 eruption period of Unzen volcano can be divided into three stages with respect to temporal SP changes. The three stages defined in this section are indicated by bars in the right-most column of Fig. 2 and by numbers at the bottom of Fig. 8.

The first stage covers approximately four months from the late March through June 1991, which corresponds to the period from the beginning of observation to one month after the appearance of the lava dome. In this period the continuous recording data at B, C, D, E and F are available (See Fig. 3). There was unfortunately no observation in the northern part of Fugen-dake in this period because repeated measurement system was not yet fully prepared. Let us see the temporal change of SP profiles along a path from the lava dome toward southwest direction in the first stage. Monthly averaged SP values were plotted versus the horizontal distances between each station (B–F) and former-Jigoku-ato crater (or the lava dome) in the upper panel of Fig. 4. The SP profile of August 1991 was also plotted together so that a reader can see the profile including stations G and G', though it does not belong to the first stage in our definition. The profile of topographic elevation is also shown in the lower panel of Fig. 4. Figure 4 gives us two
Fig. 4. Monthly averaged SP profiles (upper panel) and topographic elevation along the path crossing sites B–G' in Fig. 3 (lower panel). The horizontal axis is the distance between each site and the center of the former Jigoku-ato crater. The potential at site B is assumed to be fixed.

pieces of important information. First, the SP has increased approximately 500 mV at stations D, E and F during the four months since March to June. Secondly, the SP is higher toward the lava dome (with increasing topographic height). Terrain-related self-potentials or so-called 'topographic effects' generally have negative correlations with topographic elevation, namely, lower potentials with higher elevations. Hence the high SP near the dome detected here seems to be positively anomalous. Unfortunately we have no data of stations G and G' before August and hence we don't know how much was the SP increase at these two stations during the first stage. However, considering the large positive anomaly near the dome observed in August, stations G and G' are also inferred to have had considerable increase in SP in the first stage.

The second stage covers two and a half years from July 1991 to December 1993, during which the lava dome erupted in an exogenous manner. Equipotential maps of SP in December of 1991, 1992 and 1993 are shown in Figs. 5(a), (b) and (c), respectively. Although noticeable temporal SP changes were detected also after the first extrusion of the dome, basic features of spatial SP distributions were stable through all stages of the eruption. Namely, all the equipotential maps in Fig. 5 have three positive SP regions (H1, H2 and H3) and one negative SP region (L1). As has been pointed out in Hashimoto and Tanaka (1995), H1 and H2 are thought to be terrain-related potentials, referring to the following two facts; 1) the equipotential lines roughly trace the topographic contours, 2) higher SP at lower topographic elevation. Meanwhile, as is described in the previous paragraph, positive SP H3 which lies in the vicinity of the lava dome cannot be attributed to the topographic effect. Although the equipotential lines are not closed, anomaly H3 seems to be the western half of a concentric anomaly centered at the dome, which exceeds
Fig. 5. Self-potential distributions in December of (a) 1991, (b) 1992, (c) 1993 and (d) 1994. Potentials of each map are referred to Nita pass (a dot in a circle) and are indicated in millivolts. Results of extra-surveys (broken lines in Fig. 3) have also been compiled in these SP maps.
1000 mV in magnitude over 500 m in spatial size. This positive SP is probably attributed to the streaming potential caused by subsurface hydrothermal upflows (Hashimoto and Tanaka, 1995). Electrochemical coupling or thermoelectric coupling cannot produce such a large potential and is excluded from the possible mechanisms in this case. The author observed a gradual growth of H3 in the second stage (See how a contour line of +1000 mV has moved in Figs. 5(a) and (b), for example). On the other hand, negative SP region L1 was gradually enlarged northwards and intensified in its magnitude with time. It reached to the maximum intensity in December 1993, and as a result, the SP distribution around Unzen became more dipolar featuring with a pair of anomalies H3 and L1 as we see in Fig. 5(c). Let us see the difference between two equipotential maps in order to see the temporal change in the second stage more precisely. The difference between December 1991 (Fig. 5(a)) and December 1993 (Fig. 5(b)) is shown in Fig. 6(a). The SP decrease in the second stage seems to have taken place around the site 15 (500 m west of the dome; see also Fig. 3) with the extent of approximately 500 m in spatial size. The maximum decrease in this period amounted to 500 mV. On the other hand, a SP increase seems to have occurred around the southwest of the lava dome. The maximum increase observed in the second stage was 300 mV. The spatial extent of this SP increase is not clear because the contours do not close by themselves. However, if we regard the area of higher than +200 mV as the southwestern half of the SP increasing zone, its spatial extent is comparable to that of the SP decreasing zone mentioned above. The SP changes detected in the summit area of Unzen can be grouped into two distinct types, namely, the northern type (typically observed at site 15) and southern type (typically observed at site D; See also Fig. 8). The trend of increase at southern sites changed remarkably after the first dome extrusion. For instance, the trend of increase at site D in the first and second stages are approximately 5.7 mV/day and 0.2 mV/day, respectively. Besides, we can recognize SP decrease at northern sites in the second stage. The trend of SP change at site 15, where the most significant decrease was observed, is about −1.4 mV/day.

The third stage originates in January 1994, after which the manner of dome growth became

Fig. 6. Spatial distribution of SP changes (a) in the second stage and (b) in the third stage.
endogenous and the volcanic activity progressively receded. The SP map in December 1994 is shown in Fig. 5(d). Broken contour lines indicate that they were interpolated. Measurements in the vicinity of the dome were impossible in this period because of the frequent collapse of lava and rapid growth of the dome. In the third stage, self-potentials at southern sites continued to increase at first with their trends getting rather steep again, then almost stopped to increase after 1995. Meanwhile, SP at northern sites reversed into increase at first, and then, almost ceased their changes also after 1995. In Fig. 6(b) we show the distribution of the difference between December 1993 and August 1995, in order to see the temporal change in this stage. Here we use the SP map of August 1995 instead of December 1994 map shown in Fig. 5(d) because the latter does not have the data in southwestern part of the dome. It was clarified by Fig. 6(b) that the temporal SP changes had concentric pattern with its center at the southwest of the lava dome. The amount of the change was more than 300 mV over spatial extent of 800 ~ 1000 m.

The observed temporal SP changes are quite large and it is obvious that these changes are associated with volcanic activity of Unzen by the following reasons. At first, seasonal variation of terrain-related potentials is unlikely to be a possible cause in this case. We do not see any obvious annual variations in the time series of SP for more than four years nor the correlation with the precipitation which is plotted together in Fig. 8. It is obvious that the seasonal precipitation changes do not severely affect the SP in this case. Secondly, such large temporal SP changes are restricted to the area less than 1 km from the lava dome. In fact, it is clear that SP is quite stable in distant areas comparing the results of two surveys conducted by NEDO (New Energy Development Organization) (1988) and Hashimoto et al. (1995). Hence the detected SP changes in the summit area of Unzen should be those of volcanic origin and they cannot be a part of regional changes of larger scale.

4. Discussion

4.1 Mechanism of SP change

4.1.1 Streaming potential associated with fumarole

The electric streaming potential is caused by selective ion transport (or convection current) with fluid flow along a solid-liquid interface in a porous medium (in ordinary conditions in the earth's crust, positive charges are transported with fluid flow). Electric current sources in positive/negative signs appear in the region where the streaming potential coefficient (efficiency of charge transport) effectively decreases/increases along a flow path (Ishido, 1989). There are some causes of the change in the streaming potential coefficient. For instance the magnitude of the streaming potential coefficient has positive correlation with the temperature of the system (Ishido and Mizutani, 1981) and hence temperature change along a flow path can bring about a heterogeneity of the streaming potential coefficient. Another example is the fluid flow crossing the ground surface; the streaming potential coefficient on the air side should be considered as zero.

Associated with the fumarolic activity in Unzen volcano, positive current sources are expected in relatively shallow zones beneath the fumarole areas. Positive current sources are thought to be produced partly by the temperature decrease and resulting decrease in the streaming potential coefficient along the upflow path. In the upper part of the upflow region, the liquid/vapor two phase flow changes into the single-phase vapor flow due to pressure decrease as the ground surface being approached. Since electric charge cannot be carried by the flow of the steam phase alone, positive charge carried by the liquid phase upflow from depth will accumulate around a zone where separation between the vapor and the liquid phases occurs. This is thought to be the main cause of the positive current sources at shallow levels. In the following subsections, we will discuss the evolution of hydrothermal fluid flows associated with the volcanic activity and try to explain the observed changes in SP by electrokinetic mechanism.
Fig. 7. Schematic illustrations of east-west cross sections showing equivalent electric current sources associated with fluid flow in (a) the first stage, (b) the second stage and (c) the third stage. Arrows indicate fluid flow.

SP profiles measured on the ground surface contain terrain-related potentials and probably regional background anomalies due to geological inhomogeneity. It is desirable to remove these potentials in order to make clear the streaming potentials of volcanic origin. Some investigators adopted the first-order correction for topographic effect by assuming a constant SP gradient versus topographic elevation throughout the survey area. However, such kind of topographic correction is not always effective in a field with strong heterogeneity in geophysical conditions.
such as the permeability, electrical resistivity and so on. In the case of Unzen, the topographic effect is $-7 \sim -10$ mV/m around anomalies H1 and H2 shown in Fig. 5. A linear topographic correction with such a large coefficient substantially distort other SP features. Hereafter, we evade this problem by considering only the difference of SP distributions (this is thought to be possible since background anomalies did not change largely with time as described in the previous section).

4.1.2 First stage (late March through June 1991: growth of hydrothermal upwelling accompanying magma ascent)

Magneto-Telluric surveys conducted by Joint University Research Group have revealed that an aquifer exists widely below Shimabara peninsula at the depth between $-1.0$ km to $+0.5$ km above sea level (ASL) (JURG, 1992). Kagiyama et al. (1995) estimated the speed of magma ascent as 20 m/day and proposed an idea that a phreatomagmatic explosion on April 9, 1991 took place when the magma head reached the upper level of the aquifer. According to his estimation, the magma head was ascending between the upper level of the aquifer and the ground surface in the first stage. Considering the mixing of much meteoric water in fumaroles (inferred from isotope analysis of volcanic gases by Hirabayashi, pers. commun.), ground water around the magma vent was probably heated and a convective flow in the aquifer developed as illustrated in a schematic model, Fig. 7(a). This hydrothermal convection should have produced electric current sources of positive sign at the upper level and of negative sign at the lower level of the aquifer.

Resistivities of shallower levels than $+0.5$ km ASL are quite high except the vicinity of active craters (JURG, 1992). However, most of the shallow levels are thought to be saturated with ground water since the large topographic SP effect is present in the summit area of Unzen. The high resistivities are probably due to low salinity of shallow ground water and lack of altered minerals. As the magma head was rising toward the ground surface, upward flow was induced along the magma vent in the shallow water-bearing zone. This upflow produced positive current sources near the magma head, resulting in the rapid SP increase in the first stage (see Fig. 7(a)).
The current sources produced in the shallow level are thought to be more effective for large SP on the surface than the deep sources produced in the upper level of the aquifer.

Signatures of magma ascent were also detected by other observations. Significant changes were seen in the slope distance on the south of Fugendake measured by electronic distance measurement network (Geological Survey of Japan and Unzendake Weather Station, 1995) and the geomagnetic total force observed with proton magnetometers (Tanaka et al., 1995) around May 1991 as shown in Fig. 8. Remarkable decrease in slope distances on the south of Fugendake meant the ground dilatation before the appearance of the dome. Tanaka et al. (1995) explained the geomagnetic changes in this period by the effect of replacement of magnetized igneous rocks by nonmagnetic magma body which intruded to the shallow part. It is plausible that hydrothermal upflow associated with rapid SP changes was enhanced by the shallow intrusion of the heated body and consequent ground dilatation.

4.1.3 Second stage (July 1991 to December 1993: establishment of shallow hydrothermal convection)

The second stage is considered as the period of establishment of a shallow hydrothermal convection involving peripheral ground water which was gradually heated by the magma having intruded in the first stage. After the shallow intrusion of magma, quasi-steady thermal supply from the magma heated up the peripheral ground water and established a convection in the shallow level. The upwelling near the heat source (magma) needed fluid supply from the surrounding zone and resulted in the appearance of descending flow of ground water in the surrounding areas as illustrated in Fig. 7(b). Positive current sources beneath the lava dome kept growing, while negative sources appeared where meteoric water started to percolate into the ground. These positive and negative current sources are thought to have brought about the dipolar SP change observed in the second stage shown in Fig. 6(a).

A resistivity mapping by bipole-dipole electric soundings of the western part of Myoken caldera (including Kunimi-dake and Myoken-dake) was carried out in May and June 1995. The total field apparent resistivity is defined as \( \rho_a = |E|/|J| \), here \( E \) is the measured electric field vector at a certain position and \( J \) represents the theoretical current density vector that would be generated over a uniform half space (Keller et al., 1975). As seen in Fig. 9, the apparent resistivity decreases from west to east on Fugendake and the highest apparent resistivity appears in the middle. This is easily understood if we assume the contact of high resistivity in the west side and low resistivity in the east side. This result is also supported by an air-borne electromagnetic survey by Mogi et al. (1995). The negative pole of the dipolar SP change is located in the lower side of this resistivity boundary, where the permeability is relatively high and meteoric water is likely to percolate downward.

4.1.4 Third stage (January 1994 to 1995: lateral expansion of upwelling area)

The third stage is characterized by endogenous growth of the lava dome with remarkable ground deformations (Geological Survey of Japan and Unzendake Weather Station, JMA, 1995), which implies a shallow ground dilatation. The endogenous growth occurred under the condition of a vent chocked with viscous magma. Then the magma beneath the ground surface pushed the lava dome looking for its exits. SP changes on the ground surface showed concentric increase with its center at the southwest part of the dome as shown in Fig. 6(b). This spreading of high SP region can be attributed to the lateral expansion of upwelling portion of the hydrothermal convection which was established in the previous stage (Fig. 7(c)).

It is noteworthy that the beginning of the third stage almost coincides with the rapid changes in the geomagnetic total field (Fig. 8) and the ground deformation. As for the geomagnetic changes Tanaka et al. (1995) proposed a model of an equivalent demagnetized sphere close to the ground surface at about 200 m west from the lava dome. They pointed out that the thermal (de)magnetization is one of the most important mechanisms for local geomagnetic changes
Fig. 8. Time series showing the rainfall at Unzendake Weather Station, Japan Meteorological Agency (about 4 km SW of the lava dome) (top panel), the geomagnetic total force measured with proton magnetometer at stations close to the lava dome (after Tanaka et al., 1995) (second panel) and the self-potentials at sites 15 (third panel) and D (bottom panel). Three stages of SP changes are also indicated at bottom.
in the case that hydrothermal fluid motion is a dominant process of subsurface heat transfer. The significant decrease in slope distances means the lateral expansion of the lava dome. From these observations, it is clear that the manner of dome growth strongly affected the heat transfer process in the shallow subsurface zone. Namely, under the capped condition of the dome, the hydrothermal upflows and hot volcanic gases expanded laterally looking for a way out, and consequently, caused the thermal demagnetization of peripheral igneous rocks. This idea supports the fluid flow model shown in Fig. 7(c) in the third stage.

The pattern of lava effusion in the third stage is thought to be similar to that in the first stage on the point that the upper part of the magma vent was plugged (by igneous rocks in the first stage and by viscous lava in the third stage). The features of SP changes in the two stages resemble each other on the point that their centers of increase are both located in the southwestern part of the lava dome. This leads us to an idea that fractures or steam vents exist in the shallow zone under the southwestern part of the dome. Volcanic gases or hot steam might have ascended along the fractures when the main outlet was capped with viscous lava.

4.2 Time scale of hydrothermal system evolution

Many investigators have dealt with basic problems of fluid flow or heat transfer in a porous medium. For example, Elder (1967) investigated the evolution of hydrothermal convection cells in a rectangular porous medium heated from below. He numerically calculated the start-up time of hydrothermal convection.

Active volcanoes are suitable fields to investigate such transient phenomena of subsurface
hydrothermal systems. Especially, eruption of Unzen in 1990 is regarded as a good example of abrupt input of thermal source into a porous media. In the summit area of Unzen volcano the existence of a shallower water-bearing layer is inferred in addition to the deeper aquifer as mentioned in the previous section. Shallow hydrothermal convection has probably grown in this layer in the second stage as shown in Fig. 7(b). Here we regard the SP decrease in the negative portion of the dipolar change reflecting a start-up process of hydrothermal convection and try a simple estimation. The least-square fit of the temporal SP change at site 15 in this stage to the exponential decay curve gives the characteristic time constant of about 500 days. The characteristic value of convection-induced velocity in a liquid-saturated porous medium is given as,

$$v_R = \frac{\kappa R_a}{L} = \frac{gk\alpha \Delta T}{\nu}$$

(1)

where $k$, $R_a$, and $L$ are the thermal diffusivity, Rayleigh number and characteristic size of the system, respectively. Symbols $g$, $k$, $\alpha$, $\nu$ and $\Delta T$ denote the gravity acceleration, permeability, coefficient of cubical expansion, kinematic viscosity of the permeating fluid and impressed temperature difference given in the system (Garg and Kassoy, 1981). Therefore, non-dimensional characteristic time can be written as,

$$t^* = \frac{v_R}{L} t = \frac{gk\alpha \Delta T}{L \nu} t$$

(2)

where $t$ is characteristic real time. According to Elder (1967) the non-dimensional characteristic start-up time of transient convection is several tens. Substituting $t^* = 10$, $t = 500$ days (4 x 10^7 sec) and $L = 500$ m into Eq. (2), we get $v_R$ as 1 x 10^{-4} m/sec (9 x 10^6 m/day) in the case of Unzen volcano, though this estimation is rough and has some differences in configuration of the system from Elder’s work. The estimated convection-induced velocity is thought to be significantly larger compared to those in typical geothermal systems (10^{-2} ~ 10^{-1} m/day; Garg and Kassoy, 1981).

In Unzen the shallow zone around the magma vent should be highly fractured and hence, have especially large permeability. In fact, substituting $\alpha = 2 \times 10^{-4}$ K^{-1} and $\nu = 1 \times 10^{-6}$ m^2/sec (both are for water at 20°C) as those at a specific reference location of the system, $\Delta T = 1000$ K and $g = 9.8$ m/sec^2 into Eq. (2), we estimate the permeability of the system as $6 \times 10^4$ darcy ($6 \times 10^{-11}$ m^2), which is quite larger compared to that of a typical hydrothermal system in geothermal areas (0.01 ~ 0.1 darcy).

### 4.3 Other possible causes of SP generation

Self-potential change is also produced by other processes besides the electrokinetic coupling. Several mechanisms have been proposed by former investigators such as the effects of electrochemical concentration cells, oxidation-reduction reaction and the thermoelectric coupling. We are going to examine the possibility of these mechanisms for explanation of the SP anomalies and their temporal changes in Unzen.

Corwin and Hoover (1979) reported that the electrochemical coupling does not produce potential difference grater than several tens of millivolts and hence, we can rule it out for the cause of the major SP anomalies or their temporal changes observed in Unzen.

Thermoelectric coupling can produce both positive and negative potentials. However, we have poor knowledge about the thermoelectric coupling coefficient of the subsurface rock/water system so that further quantitative discussion will be suspended at present. The thermoelectric coupling effect might be partly responsible for the major SP anomaly in the vicinity of the lava dome because there must be substantial amount of temperature gradient around the magma vent.

The oxidation-reduction effects over mineral deposits in many cases result in negative SP anomalies on the ground surface. Hence it cannot be the cause of the major positive anomaly in Unzen. Such effect is normally due to the difference in the oxygen concentration between shallow
and deep levels. Sato and Mooney (1960) suggested this process may produce a potential of 400 mV in the maximum case. However, SP anomalies produced by this kind of mechanism should be rather stable and cannot explain the rapid temporal SP changes in Unzen.

There is a possibility that the injection of volcanic gases into the shallow levels induces the oxidation-reduction effect. For instance, changes in the chemical contents of aqueous solution caused by mixing of volcanic acid gases into local ground water might have caused a local negative SP anomaly (Massenet and Pham, 1985). To our present knowledge, however, there is no positive evidence suggesting the local injection of volcanic gases into the shallow levels of the SP decreasing region.

5. Conclusions

The author investigated the self-potential in association with the 1990–1995 eruption of Unzen volcano. The intensive upwelling of hot ground water is believed to be the primary cause of the major positive SP anomaly, which was found in the vicinity of the newly extruded lava dome. Temporal variations of SP were also recorded through continuous observations and repeated surveys. We inferred how hydrothermal systems beneath the volcano developed. The eruption period can be divided into three distinct stages with reference to the SP changes, and each stage can be characterized by the different manner of the evolution of hydrothermal systems. The shallow levels in the summit area of Unzen is thought to have high permeabilities on the basis of the time constant of the dipolar SP change observed in the second stage, which indicates the establishment of a shallow hydrothermal convection as a result of abrupt input of a heat source.

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