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Change in the Shallow Resistivity Structure After 1995 Eruption at Kuju Volcano, Japan

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ABSTRACT

We have been conducting several geophysical observations at Kuju volcano, in the central part of Kyushu Island, Japan, since the 1980's. After the phreatic eruption in 1995, we carried out gravity measurements and magnetic surveys to monitor the internal thermal state of the volcanic body. We also drilled two boreholes in 1991 and 2001 to obtain volcanic steam. Within ten years, the temperature of the shallow steam reservoir decreased more than 130 degrees. Prior to the drilling in 1991, we carried out an electrical prospect to determine the drilling point. In 2001, another electrical survey was carried out to investigate the cause of this rapid temperature change. Two inverted resistivity models revealed that the superheated reservoir was cooled and liquefied. From the combined interpretation of the geophysical observations and the repeat electrical survey, it was concluded that the cold meteoric water is cooling the whole volcanic body.

1. INTRODUCTION

Kuju volcano is situated in the central part of Kyushu Island, southwestern Japan. In the central part of the volcano, there exists an active fumarolic field, which is one of the most active fumaroles in Japan (Fig.1). We have been carrying out several geophysical monitorings such as surface temperature, micro-earthquake observations since 1980s. In 1990, we have started the repeat gravity measurements in this area. Ehara (1992) conducted a hydrothermal fluid flow simulation of this area based on the observation results and succeeded in constructing the hydrothermal model that can consistently explain the heat discharge rate and the geophysical observations.

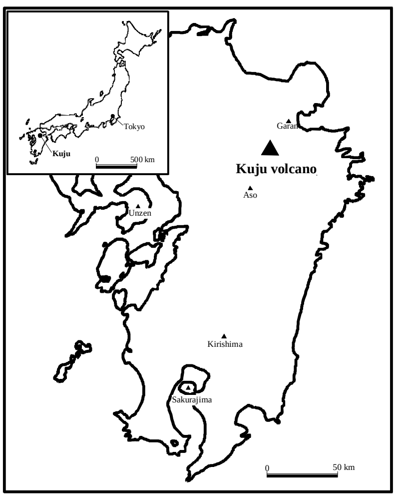

Figure 1: Location Map of Kuju Volcano

A phreatic eruption occurred near the fumarolic field in 1995, and the steam discharging is still active. After the phreatic eruption, other geophysical and geodetical observations such as geomagnetic survey, ground tiltmeter monitoring, GPS measurements have carried out and we are accumulating this data.

In 1991, we drilled a short distance borehole to obtain superheated steam from the shallow reservoir. Prior to the drilling, we conducted an electrical prospecting. We drilled toward the highly resistive zone and succeeded in obtaining superheated steam. The temperature of the steam was 233 degree C at the wellhead. In 2001, we drilled another borehole toward the center of the resistive anomaly, but the wellhead steam temperature was 98 degree C. In 2002, another electrical prospecting was carried out to investigate the cooling of the reservoir. The inverted result was completely different from that of 1991. This implies that the superheated reservoir was cooled and liquefied.

In this paper, we describe the results of geophysical observations, especially the resistivity surveys in 1991 and 2002, and discuss the cooling process of the Kuju volcano after 1995 phreatic eruption. First, we describe the results of electrical prospecting in 1991 and 2002 in detail, and give an interpretation of the thermal state change at the shallower region. Then we will compare the interpretation with those deduced from the repeat gravity and repeat magnetic survey, which corresponds to the thermal state change of bigger scale.

2. RESISTIVITY PROFILING AND DRILLING

2.1 Resistivity Profiling in 1991

Prior to the drilling in 1991, a resistivity survey and 30cm depth temperature measurements were carried out (Mogi, 1994) to select the location of the borehole. Fig.1 shows the measurement line.

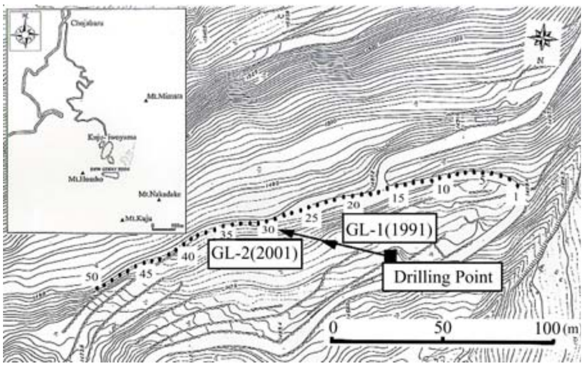

Figure 2: Measurement Line of the Resistivity Profiling. Arrows indicate borehole trajectories.

Figures GL-1 and GL-2 show the location of the borehole, and the solid rectangle shows the wellhead, and the numbers show the electrode positions. Table 1 summarizes the details of the resistivity survey in 1991 and 2002, and Fig.3a) shows the inverted resistivity section. The inversion algorithm used was the smoothness constrained least squares inversion using ABIC for the criterion of choosing damping factor (Uchida, 1993).

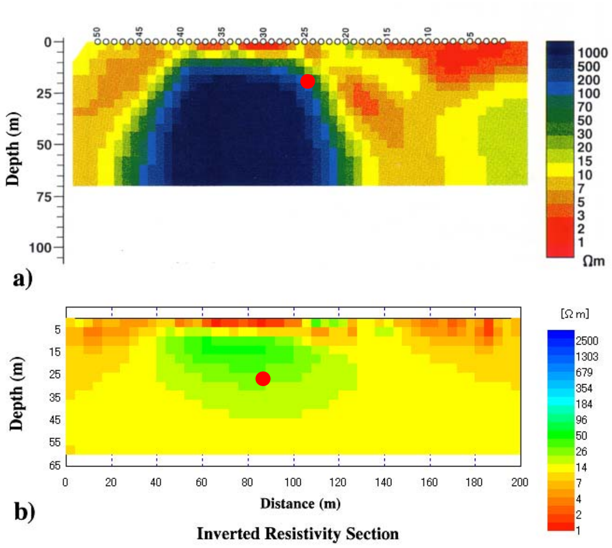

Figure 3: Inverted Resistivity Sections

a) in 1991 and b) in 2002,

Table 1: Specifications of the Resistivity Profiling

Year	1991	2002
Survey Line Length	200m	200m
Electrode Interval	4m	4m
No. of Electrodes	51	51
Array Configuration	Wenner, Eltran	Pole-Pole
Depth of Investigation	50m	60m
Inversion Algorithm	Smoothness Constrained inversion with ABIC	Smoothness constrained NLCG

From Fig.3a), one can see that the low resistivity zone (about 10 ohm-m) is distributed throughout the section. This indicates hydrothermal alteration of rocks caused by the geothermal activities. One remarkable feature is a highly resistivity body over 1,000 ohm-m at the depth from 10m to 70m in the central part of the section. The resistivity contrast between the anomalous body and the surrounding zone is over a hundred. As the surrounding zone was highly altered, it is unlikely that intact rocks are distributed in this area. The high resistivity zone was interpreted as a superheated steam reservoir (Mogi et al., 1994). Near the electrodes No.27 and Nop.34, one can see that the relatively high resistivity zones elongate from the reservoir to the surface, which can be interpreted as the paths of stream. The high temperature anomaly deduced from the 30cm-depth temperature measurements showed good agreement with the surface fumaroles distributions. This means that high temperature steam exists just beneath the ground surface.

Based on these interpretations, a borehole (GL-1) was drilled as shown in Fig.2. The length of the borehole was 27m, and the depth of the bottom hole was 18m from the surface. Although the bottom hole did not reach to the center of the reservoir, we succeeded in obtaining superheated steam of 233°C at the wellhead.

2.2 Resistivity Profiling in 2002

After the phreatic eruption, we drilled a longer borehole (GL-2) near the borehole GL-1. The length of GL-2 was 47m, and the depth of the bottom hole from the surface was approximately 30m. The drilling was directed toward the center of the resistive reservoir, which was detected in 1991, to obtain higher temperature steam. Nevertheless, the highest steam temperature was about 98°C, which corresponds to the boiling point at the altitude of the drilling site.

To investigate the cause of such temperature change, we carried out repeat measurements of 30cm-depth temperature and resistivity on the same measurement line as that of 1991. The specifications of the repeat survey in 2002 are also shown in Table 1. In the resistivity survey in 2002, pole-pole configuration was used. For the analysis of the resistivity data, we developed a new inversion code based on the nonlinear conjugate gradient optimization technique. The inversion result is shown in Fig.2b). This figure reveals that the resistivity of the reservoir decreased from 1,000 ohm-m to several tens of ohm-m. The general features of the surrounding area are unchanged. That is, the two surface resistivity distributions are almost identical, and one can see the paths of steam in both the 1991 and 2002 models.

Fig.4 shows the comparison of the 30cm-depth temperature profile obtained in 1991 and 2002. The change in the 30cm-depth temperature profile is not as clear as the resistivity change. At some sites such as No.17, 19, and the interval from No.23 to No.28, temperatures in 1991 were higher than those of 2002. However, roughly, temperatures in 2002 are lower than those of 1991, and one can see that the 30cm-depth temperature shows a decreasing tendency. Considering the fact that the drastic change occurred in the region deeper than 10m below the surface, it is quite likely that the obvious changes could not be seen on the 30cm-depth temperature. We deduced that the superheated steam reservoir observed in 1991 turned out to be a liquid dominated reservoir.

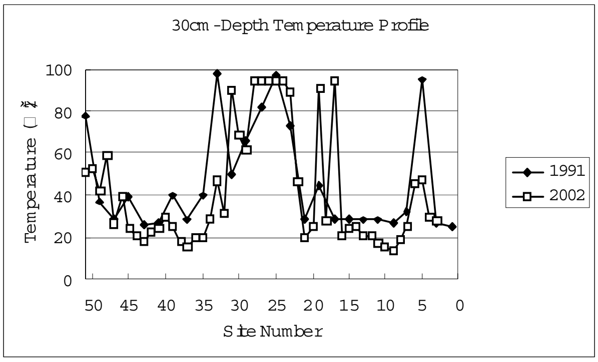

Figure 4: 30cm-depth temperature in 1991 and 2002

2.3 Resistivity Change Due to the Liquefaction of the Reservoir

The drastic change was recognized between two resistivity models obtained in 1991 and 2002, and this indicates that the superheated reservoir was liquefied. We discuss the possibility of the reservoir liquefaction causing such a drastic change in resistivity.

Bussian (1983) proposed to utilize the Hanai-Bruggeman's formula (Hanai 1962) for the evaluation of rock resistivity

$$\frac{\sigma_0 - \sigma_f}{\sigma_m - \sigma_f}\left(\frac{\sigma_m}{\sigma_0}\right)^d = \phi \qquad (1)$$

where σ_0 is the conductivity (reciprocal of resistivity) of the rock, σ_m is the conductivity of the rock matrix, σ_f is the conductivity of the pore fluid, and ϕ is the porosity. d is the characteristic coefficient in the system. Formula (1) can be transformed to

$$\sigma_0 = \sigma_m \phi^m \left(\frac{1-\sigma_f/\sigma_m}{1-\sigma_f/\sigma_0}\right)^m \qquad (2)$$

where *m* is a constant so-called cementation factor.

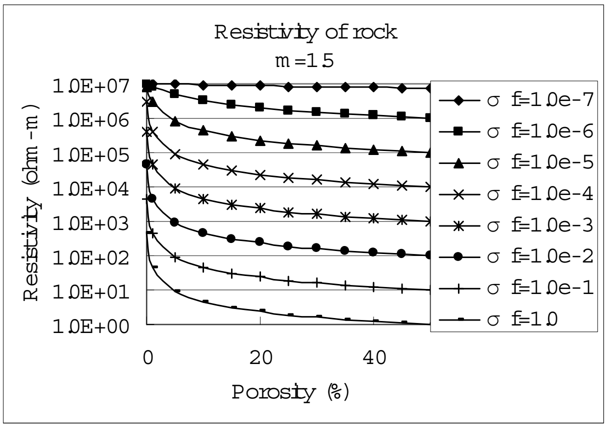

Fig. 5: Rock resistivity dependence on porosity and fluid conductivity. cementation factor m=1.5

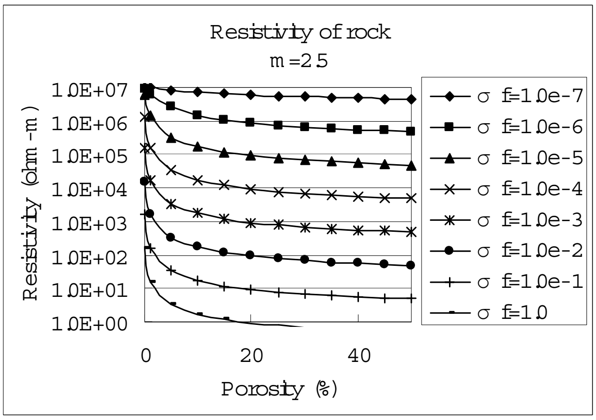

Figure 6: Rock resistivity dependence on porosity and fluid conductivity. cementation factor m=2.5

For the sake of simplicity, we expand the implicit form of formula (2) using binomial expansion up to the first order to get

$$\sigma_0 = m\sigma_f\left(1-\phi^m\right) + \sigma_m \phi^m \qquad (3)$$

To calculate the conductivity of rocks using (3), one needs to determine the conductivity of the rock matrix, pore fluid, porosity, and the cementation factor. For the conductivity of the rock matrix, we can assume them to be zero. But due to the fact that the conductivity of sand particles, taking into account the surface conduction effect, is about 10^{-7} S/m (Yamaguchi, 1962), we used this value for the matrix conductivity. For the cementation factor, m=1.5 is frequently used for the porous medium, and m=2.5 is frequently used for the cracked medium. Fig.5 and Fig.6 show the resistivity dependence of rock on various combinations of matrix conductivity, pore fluid conductivity, and porosity. According to the hydrothermal simulation result in Ehara (1992), the porosity of the rocks in the fumarolic field in Kuju volcano was estimated to be 15 to 20%. In Figs.5 and 6, one can see that if the pore fluid conductivity is higher than 0.01 S/m, the rock resistivity is below 100 ohm-m, which is the resistivity of the liquefied reservoir. The conductivity higher than 0.01 S/m is quite reasonable for the ground water in the geothermal field. It follows that the liquefaction of the reservoir is able to cause the drastic resistivity change mentioned above.

3. REPEAT GRAVITY AND MAGNETIC SURVEY

3.1 Repeat Gravity Survey

Since 1990, repeat gravity measurements have been carried out around the fumarolic field. After the 1995 eruption, gravity measurements had been carried out at each station at intervals of one week to several months. Until now we are monitoring the gravity change at intervals of several months a year.

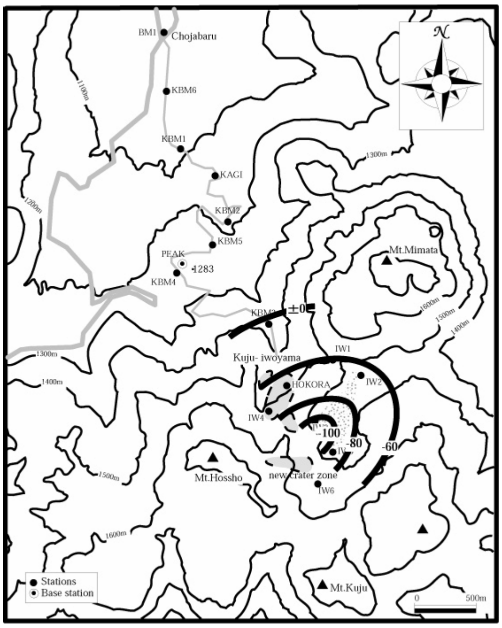

Figure 7: Spatial distributions of gravity change from October 1995 to January 1996

The spatial patterns of the gravity change after the 1995 eruption are shown in Fig.7 and Fig.8 together with the distribution of gravity stations. The gravity values quickly decreased just after the eruption, and then continued to decrease gradually for two years. In this decreasing stage, the spatial distribution of the gravity change centered around the new craters. After the decreasing stage, the gravity values gradually increased, centering around the pre-existing fumaroles.

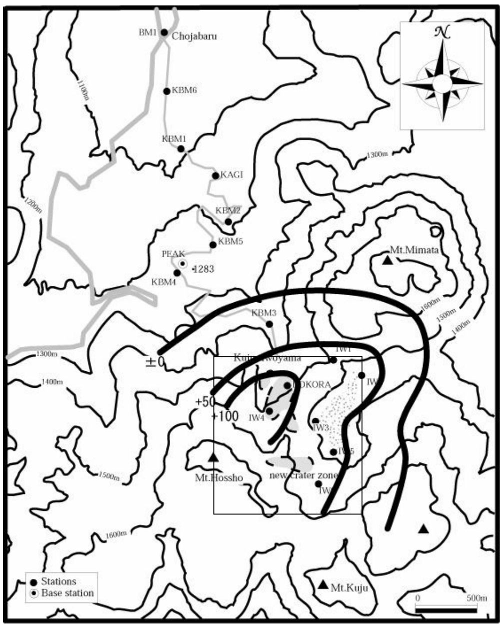

Figure 8: Spatial distributions of gravity change from Jan. 1998 to May 2001. The rectangle in the figure corresponds to the area shown in Fig.9.

Nishijima et al. (2002) evaluated the subsurface mass balance of the study area using the gravity change and the heat discharge rate at a different period. The result is summarized in Table 2. The table tells us that after 1997, recharging of cold meteoric water from surroundings increased several times from that of before 1995 eruption.

Table 2: Mass balance beneath Kuju volcano (after Nishijima et al., 2002)

Period	From Oct.1995 To Jan.1996	From Jan.1998 To May 2001
Steam Discharge 65% Meteoric 35% Magmatic	89,000 t/day	25,000 t/day
Subsurface Mass Balance	-55,000 t/day	+5,500 t/day
Magmatic Water	31,000 t/day	8,750 t/day
Recharge from Surroundings	3,000 t/day	21,000 t/day

3.2 Repeat Magnetic Survey

After the 1995 eruption, six proton magnetometers were installed around the new craters and pre-existing fumaroles by Kyoto University and Kyushu University (Sakanaka et al., 2001). Repeat magnetic measurements were conducted at more than twenty sites. At all sites, linear magnetic field changes were observed. In the southern part of the survey area, the steepest magnetic change rate was more than 40nT/year. In the northern part, the steepest magnetic filed decrease was more than 20nT/year. This spatial pattern indicates that the rock beneath the active fumarolic field is cooled and magnetized in the direction of the present geomagnetic filed (inclination 47 degree, declination N6W).

Fig. 9 shows the spatial distribution of the change of the magnetic intensity in the study area. These geomagnetic changes can be explained by a magnetic dipole in the same direction of the present geomagnetic field. We have determined the location of the magnetic source dipole using least squares. The location of the magnetic dipole was determined at approximately 400m beneath the center of the pre-existing fumarolic field. The location is shown as a star in Fig.9. This result tells us that the cold meteoric water is circulating up to several hundreds of meters.

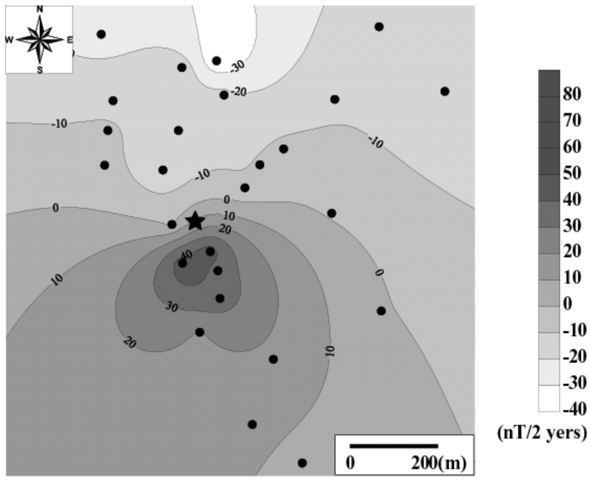

Figure 9: Spatial distributions of the magnetic variations from 2001 to 2003. Black dots indicate the measurement points, and star shape indicates the location of the source magnetic dipole. The plot area corresponds to the rectangle shown in Fig.8.

4. CONCLUSION

We have conducted several geophysical monitorings at Kuju volcano before and after the 1995 eruption. We also drilled two boreholes at the intervals of ten years. Within ten years, the temperature of the shallow reservoir decreased more than 130 degrees. This drastic change of the thermal state was detected by the repeat resistivity profiling as a disappearance of the resistive superheated reservoir. From the straightforward calculation, the liquefaction of the reservoir was able to cause a one or two digit decrease of rock resistivity. From the gravity monitoring, the circulation of the cold meteoric water was deduced. The amount of the recharging of the meteoric water was estimated to be about seven times larger than that of before the 1995 eruption. From the repeat magnetic measurements, the cooling of the volcanic body was deduced. The location of the magnetic source dipole was estimated at 400m deep in the center of the pre-existing fumarolic field. This indicates that the cold meteoric water recharged from surroundings are circulating up to several hundreds of meters deep, and cooling the volcanic body.

The shallow reservoir that was detected by the resistivity profiling exists at several tens of meters depth. This shallow reservoir liquefied accompanied by the cooling of the whole volcanic body.

REFERENCES

Bussian, A.E., : Electrical conductance in a porous medium, *Geophysics,* **56**, (1992), 107-115

Ehara, S., : Thermal structure beneath Kuju volcano, central Kyushu, Japan, *Jour. Volcanol. Geotherm. Re*s.*,* **56**, (1992), 107-115

Hanai, T., : Dielectric theory on the interfacial polarization for two-phase mixtures, *Bull. Inst. Chem. Res. Kyoto Univ*.*,* **39**, (1962), 341-367

Mogi, T., Ehara, S., Ushijima, K. and Uchida, T. : Exploration of the structure beneath fumaroles in Kuju Iwoyama, Southwest Japan., *Jour. Geothermal Res.,* **16**, (1994), 285-293, in Japanese with English abstract.

Nishijima, J., Ehara, S., and Fujimitsu, Y. : Repeated microgravity observations, GPS survey and continuous tilt measurements in Kuju volcano, *Chikyu Monthly,* **39**, (2002), 179-186, in Japanese with English abstract.

Sakanaka, S., Tanaka, Y., Utsugi, M., and Hashimoto, T. : Cooling shape of vents beneath fumaroles at Kuju-iwoyama inferred from geomagnetic changes by repeat surveys, *Scientific and Technical Reports of Faculty of Engineering and Resource Science, Akita Univ.,* **22**, (2001), 25-38, in Japanese.

Uchida, T.: Smoothness constrained 2D inversion for resistivity data by ABIC minimization method, *Butsuri Tansa,* **46**, (1986), 409-420, in Japanese with English abstract.

Yamaguchi, H.: On the relation between formation factor and surface conduction of saturated sands, *Butsuri Tansa*, **15**, (1962), 26-33, in Japanese