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# Change in the Thermal State in a Volcanic Geothermal Reservoir beneath an Active Fumarolic Field after the 1995 Phreatic Eruption of Kuju Volcano, Japan

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## ABSTRACT

Kuju volcano, which is a typical island arc volcano, is situated in central Kyushu, Japan. It has an active fumarolic field in the central part and a two-phase volcanic geothermal reservoir beneath the fumarolic field is proposed based on numerical modeling. A phreatic eruption occurred near the fumarolic field in October 1995. After that repeat geophysical measurements were conducted in and around the fumarolic field and the new craters. As a result, quick temperature decrease of the volcanic geothermal reservoir was deduced from repeat thermal and geomagnetic measurements. Repeat gravity measurements showed quick decrease around the new craters after the phreatic eruption and then gravity recovered gradually. Such temperature and gravity changes show recharge of a large amount of cold meteoric water to the volcanic geothermal reservoir. The meteoric water recharge was induced by the sudden decrease of pressure in the volcanic geothermal reservoir accompanied by the phreatic eruption. Numerical modeling of the thermal process in the volcanic geothermal reservoir after the phreatic eruption simulates the observed cooling of the geothermal reservoir very well. Such a process is very similar to the production of fluid from the geothermal reservoir without reinjection.

## 1. INTRODUCTION

Kuju volcano is situated in central Kyushu, Japan (Figure 1). It has an active fumarolic field in the central part. The volcano began to erupt on October 11, 1995 from several new craters which are about 300m south of the pre-existing fumarolic field. It erupted again in the middle of December of the same year. A large amount of steam and heat were discharged from the new craters and the pre-existing fumaroles. Various types of geophysical techniques were applied to monitor the volcanic and geothermal activities after the phreatic eruption. As a result, quick cooling of the interior of the volcano is proposed mainly by the thermal, geomagnetic and gravimetric data. Numerical modeling is applied to explain the change in the thermal process after the phreatic eruption.

## 2. KUJU VOLCANO

Kuju volcano, which is composed of many lava domes, is a typical andesitic island arc volcano. The main rock type is hornblende andesite. The volcanic activity started 0.15 Ma and the most recent big pyroclastic eruption occurred 0.05 Ma. Magmatic eruptions occurred at intervals ranging from every 1000 to 2000 years in recent 15 kys. The most recent magmatic eruption was about 2000 years ago (Kamata, 1997). Several phreatic eruptions occurred in historic times at intervals ranging from several tens to a hundred years.

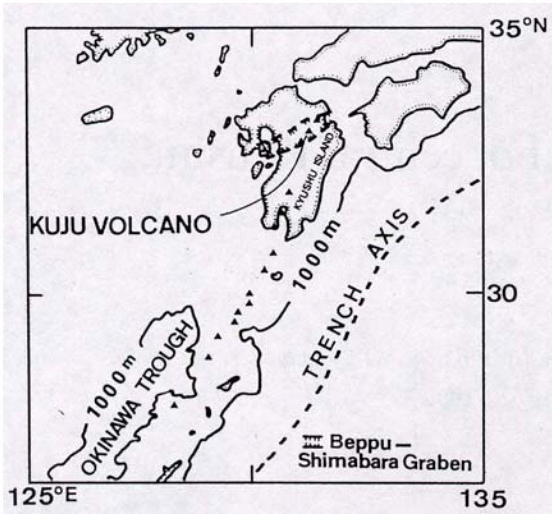



**Figure 1: Location map of Kuju volcano, central Kyushu, southwestern Japan.**

The active fumarolic field in the central part of Kuju volcano is one of the most intense geothermal fields in Japan. The natural heat discharge rate was estimated at about 100MW before the 1995 eruption and most of it is from steaming ground and fumaroles (Ehara, 1992). Temperatures of fumaroles generally exceed 200 degree C and the maximum observed temperature prior to the 1995 phreatic eruption was 508 degree C (Mizutani et al., 1986).

## 3. THE 1995 PHREATIC ERUPTION

Kuju volcano began to erupt on October 11, 1995 from the new craters which are about 300m south of the pre-existing fumarolic field (the first eruption). The volume of ashes discharged by the eruption is about 20000m$^3$. The following eruption in mid-December produced about 5000m$^3$ ashes (the second eruption). After these eruptions, a large amount of steam and heat started to be discharged from the new craters and the pre-existing fumarolic field (Figure 2). Such discharge is still continuing at present (May 2004). The eruption was considered to be a phreatic eruption, because there has been no magmatic activity at the surface.

## 4. GEOPHYSICAL MEASUREMENTS AFTER THE 1995 PHREATIC ERUPTION

Several kinds of geophysical measurements such as thermal, gravimetrical, geomagnetic, electric, seismological, geodetic etc, have been conducted after the 1995 phreatic eruption. In this paper, the geophysical measurements which have close connection with the thermal process were summarized.

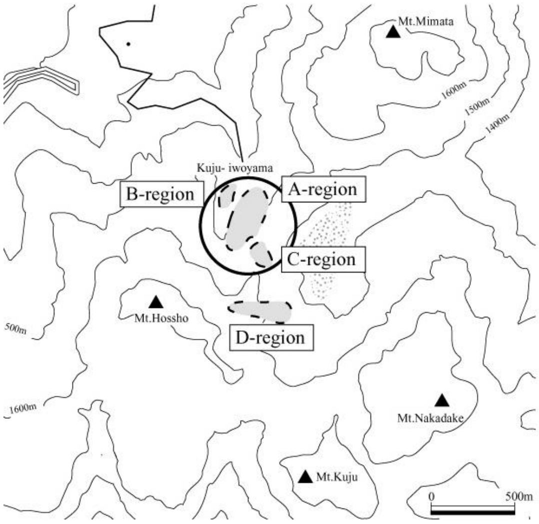



**Figure 2: Location map of the new craters (D-region) and the pre-existing fumarolic field (A,B,C-regions) in the central part of Kuju volcano.**

### 4.1 Surface Temperature

Representative temperature variations in the pre-existing fumaroles are shown in Figure 3. Pre-existing fumaroles show quick cooling of the interior of the volcano after the phreatic eruption. Figure 3 also shows the gradual increase of fumarolic temperatures before the 1995 phreatic eruption. The temperatures of the new craters also showed similar patterns except for the short period between the first and second eruptions. Most of the surface temperatures decreased after the phreatic eruption as shown in Figure 3, except those at the central part of the pre-existing fumarolic field where the surface temperatures have increased gradually since the next year after the second eruption.

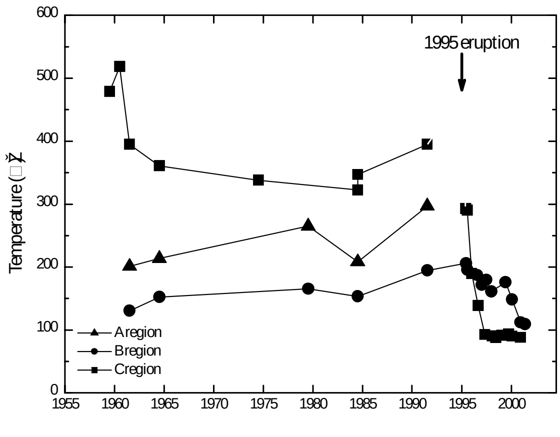



**Figure 3: Representative patterns of the pre-existing fumarolic temperatures before and after the 1995 phreatic eruption.**

### 4.2 Steam and Heat Discharge Rates

Steam and heat discharge rates from the new craters and the pre-existing fumaroles were estimated by the remote sensing technique developed by Jinnguuji and Ehara (1997). The total observed steam discharge rates and heat discharge rates are shown in Figure 4 and Figure 5, respectively. Both steam and heat discharge rates are very large during the first two months after the first eruption. The average steam discharge rate was about 100 kt /day and the average heat discharge rate was about 3000MW during the period. They are about thirty times larger than those before the 1995 phreatic eruption. After the second eruption in December 1995, both the steam discharge rate and the heat discharge rate decreased quickly. After that, they became almost constant as shown in the figures. The average heat discharge rates in the following period are between 500MW and 1000MW which are still several times larger than that of before the eruption.

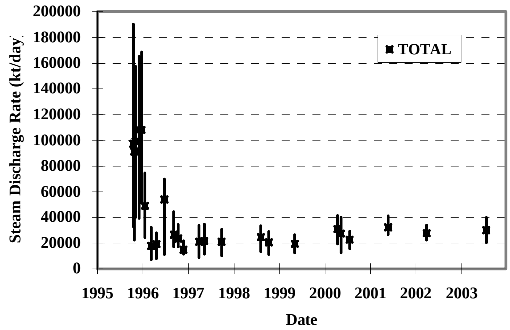



**Figure 4: Temporal variations of total steam discharge rate from the central part of Kuju volcano after the 1995 phreatic eruption.**

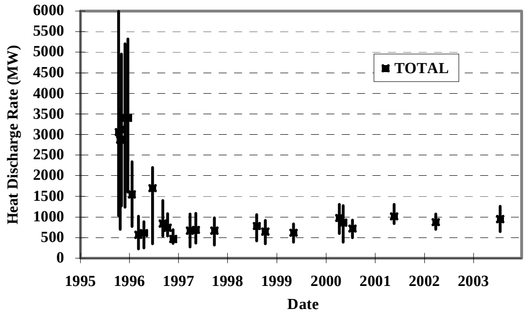



**Figure 5: Temporal variations of total heat discharge rate from the central part of Kuju volcano after the 1995 phreatic eruption.**

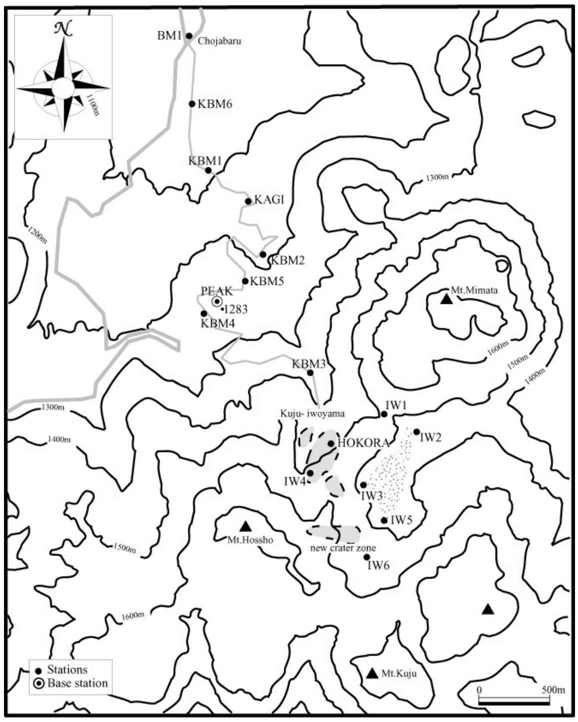



**Figure 6: Distribution of gravity stations in the central part of Kuju volcano.**

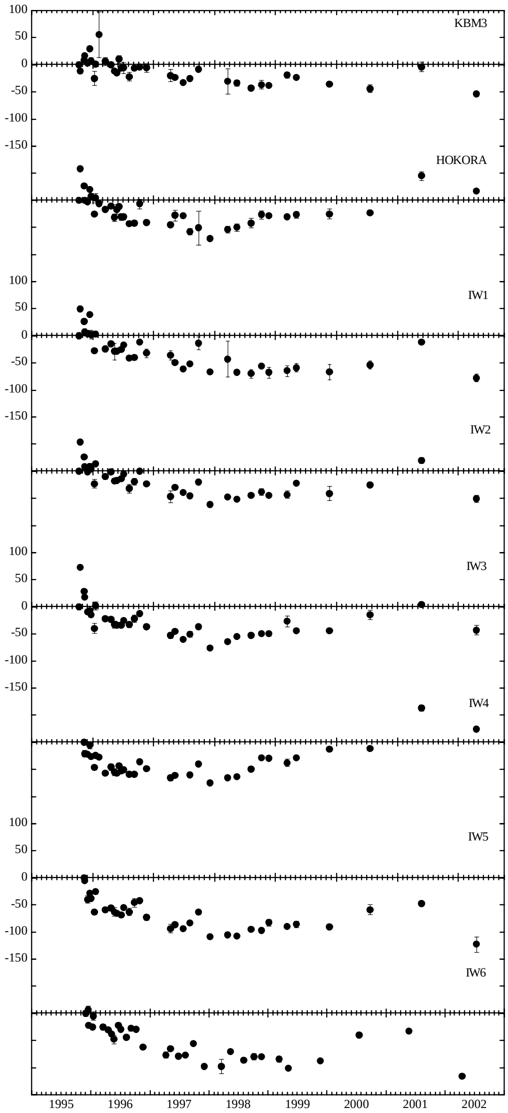
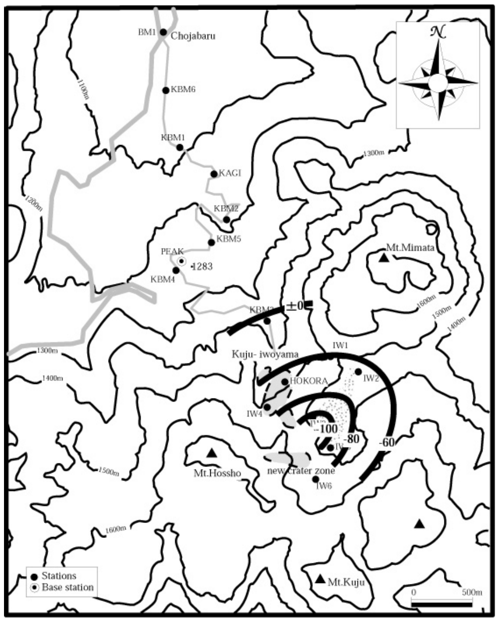



**Figure 7: Examples of gravity change in the central part of Kuju volcano (unit : microgal) .**

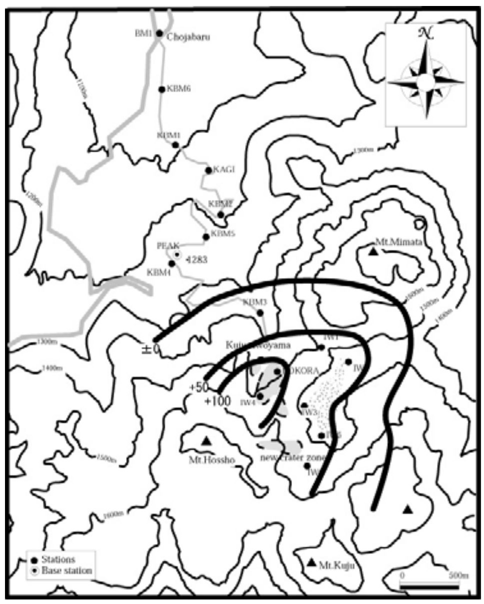
### 4.3 Gravity

Repeat gravity measurements around the new craters and the pre-existing fumaroles have been conducted at intervals of one week to several months after the first eruption by using the SCINTREX 3 and 3M gravimeters. Observation points are shown in Figure 6. Gravity values at all the gravity stations around the new craters decreased quickly during two months after the first eruption. Thereafter gravity values gradually decreased and the center of the gravity decrease moved to the pre-existing fumarolic field. The ground surface around the new craters and the pre-existing fumarolic field subsided at a rate of a few cm/year after the eruption. Therefore the effect of height change was corrected. Several examples of gravity change around the new craters are shown in Figure 7. Spatial patterns of gravity change at different periods are shown in Figure 8. Gravity decreased around the new craters and the pre-existing fumaroles during both periods. But the center of gravity decrease shifted from the new craters to the pre-existing fumaroles as shown in Figure 8.

Based on the Gauss's potential theorem (Allis and Hunt, 1986), we estimated the average mass changes at different periods, assuming the pattern of the gravity change is symmetrical. The estimated rates of mass change at different periods are -55 kt/day from October 1995 to July 1996, -2.8 kt/day from July 1996 to December 1997 and +5.5 kt/day from January 1998 to May 2001. Such changes in gravity are considered to be originated in change in water mass of the volcanic body. Accordingly, the repeat gravity measurements after the phreatic eruption show the recovery of water mass in the volcanic geothermal reservoir.




**(a)**

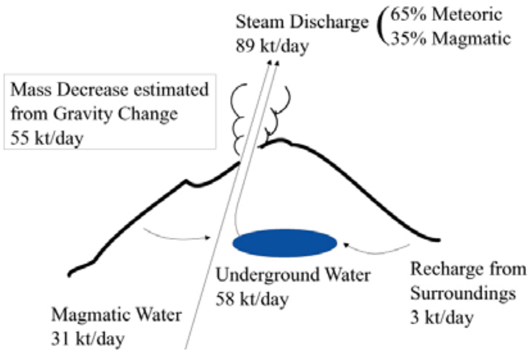



**(b)**

**Figure 8: Examples of spatial patterns of gravity change in the central part of Kuju volcano at different periods. (a) from October 1995 to January 1996, (b) from December 1997 to May 2001.**

The balance of water mass in the volcanic body was estimated by comparing the change in water mass which was estimated from gravity change and the change in the observed steam discharge rate. We assumed that the contribution of magmatic component in the discharged steam is 35% based on the isotopic study of the discharged steam (Hirabayashi et al., 1997). It means that the discharged steam from the new craters and the pre-existing fumaroles is a mixture of the magmatic steam and the groundwater vaporized by the magmatic steam. Based on the above assumptions, we estimated the water mass balance in different periods as shown in Figure 9.

Here we concentrate our discussion on the recharge rate of groundwater to the volcanic geothermal reservoir. The recharge rate of groundwater just after the eruption (from October 1995 to January 1996) was about 3 kt /day. This value is a little larger than that of before the eruption (about 1 to 2 kt /day, Ehara, 1992). After that the recharge rate of the groundwater became larger and larger, that is, 14.2 kt /day from January 1996 to December 1997 and 22 kt /day from January 1998 to May 2001. Such an increased recharge rate of cold groundwater will accelerate the cooling of the volcanic geothermal reservoir.

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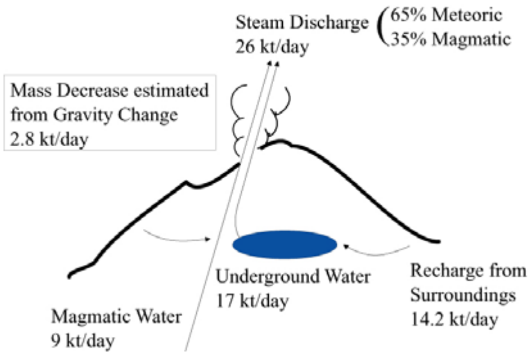


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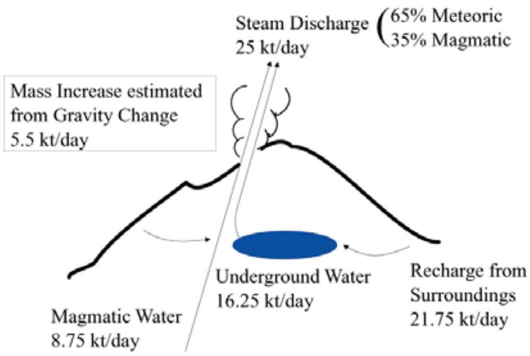



**(c)**

**Figure 9: Changes in mass balance after the phreatic eruption at different periods. (a) from October 1995 to January 1996, (b) from January 1996 to December 1997 and (c) from January 1998 to May 2001.**

### 4.4 Geomagnetic Intensity

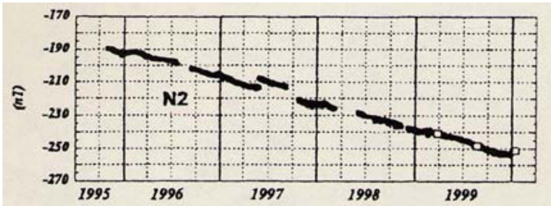
The subsurface thermal state was also monitored by continuous and repeat magnetic measurements. Six proton-precession magnetometers were set around the new craters and the pre-existing fumaroles by Kyoto University and Kyushu University (Sakanaka et al., 2001). In addition repeat measurements were also conducted at more than twenty sites in the central part of Kuju volcano.

The following changes of the magnetic field were recognized (Ehara et al., 2000, Sakanaka et al., 2001).

(a)Linear changes of total magnetic intensity were observed at all sites for eight years after the eruption (Figure . 10).

(b)The magnetic intensity increased in the southern part and decreased in the northern part of the central part of Kuju volcano (Figure 11).

(c)Magnetic changes after the eruption were very large, up to 40 nT / year.

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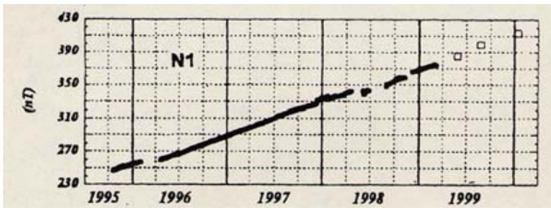



**(b)**

**Figure 10: Examples of geomagnetic changes with time after the p0hreatic eruption. (a) in the northern part, (b) in the southern part (Sakanaka et al., 2001).**

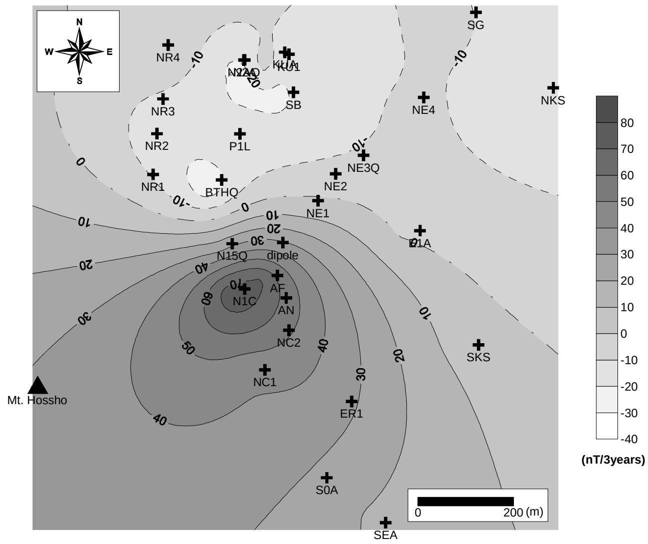



**Figure 11: Changes in geomagnetic total intensity from 2001 to 2003 on Kuju volcano.**

Thermo-magnetic, piezo-magnetic and electro-kinetic effects are generally considered as the source of magnetic change in the volcanic field. However, the magnetic changes observed on Kuju volcano were probably caused by the thermo-magnetic effect, because the decreasing fumarolic temperatures were observed and the ground surface around the new craters and the pre-existing fumaroles subsided after the phreatic eruption.

We estimated the position and the depth of the magnetic source at different periods. As a result, all the estimated positions were determined near the pre-existing fumarolic field and the depths were estimated at between 200m to 2000m deep assuming the cylindrical source. It means that the location of the magnetic source has not changed after the phreatic eruption.

## 5. MODEL OF THERMAL PROCESSES AFTER THE 1995 PHREATIC ERUPTION

In the above, we discussed the thermal, gravimetric and geomagnetic measurements after the 1995 phreatic eruption. All the data show the cooling of the volcanic body. Based on the above data, conceptual and numerical thermal models are presented in the following.

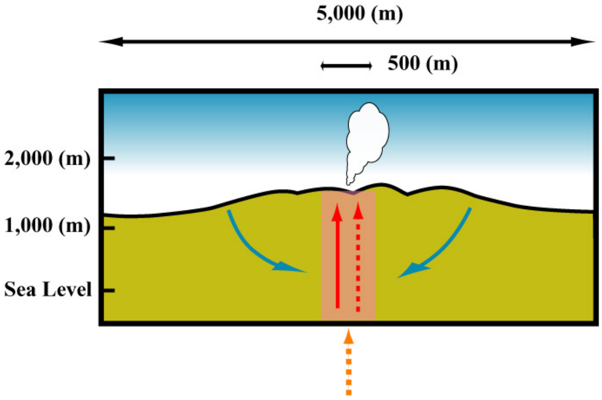
### 5.1 Conceptual Model

There are two possibilities regarding the type of the cooling heat source beneath Kuju volcano, i.e., a new magmatic intrusion or a pre-existing hot rock beneath the fumarolic field. The discharged heat was very large but we have no remarkable ground uplift before and after the eruptive activity. We observed only gradual subsidence (a few cm / year) after the phreatic eruption. Then we think that it is difficult to assume that a new magmatic intrusion exists. Furthermore, we observed the increased rate of groundwater recharge to the central part of the volcano after the eruption. Then it is possible to assume that the underground hot rock was cooled more effectively by the increased recharge rate of meteoric water after the eruption. The quick and big decrease of the pressure of the volcanic geothermal reservoir just after the phreatic eruption caused the increased recharge of groundwater. The depth of the magnetized body is estimated to be 200m to 2000m. Then we assume that the volcanic geothermal reservoir beneath the fumarolic field has been cooled after the eruption mainly by the increased recharge of cold meteoric water. Conceptual thermal models before and after the eruption are shown in Figure 12.

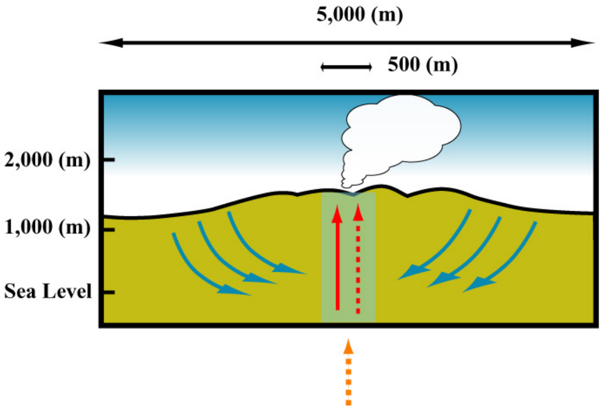
### 5.2 Numerical Model

Based on the above-mentioned conceptual model, we tried to construct a numerical model. Firstly, we constructed a natural state model before the eruption. Secondly, we constructed a post phreatic eruption model by extracting geothermal fluids from the volcanic geothermal reservoir.

In order to simulate the thermal process beneath Kuju volcano, we employed a numerical simulator developed by Hayba and Ingebritsen (1994). The simulator treats a three-dimensional finite-difference model to simulate ground-water flow and heat transport in the temperature range from 0 to 1200 degree C.




(a)

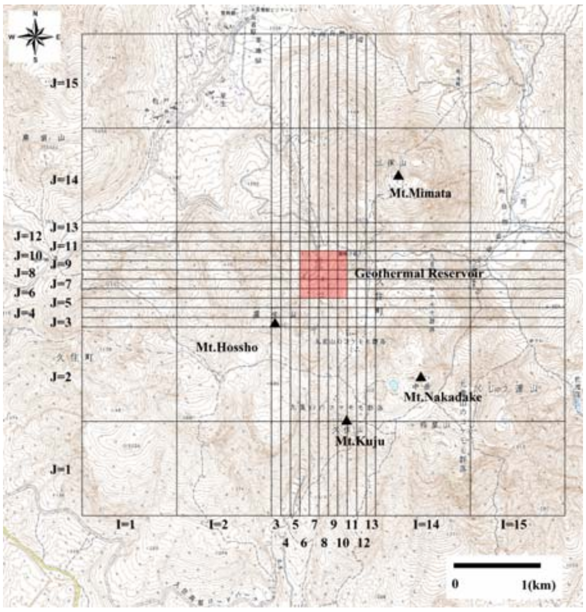



(b)

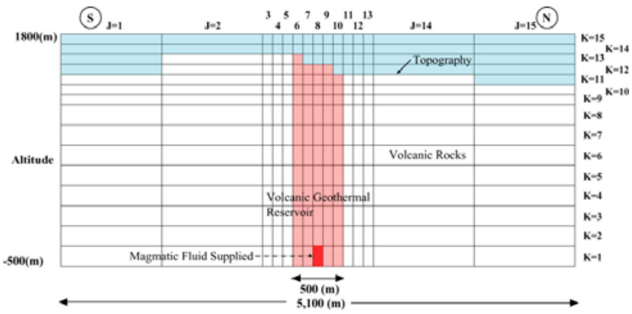
**Figure 12 Conceptual thermal models (a) before and (b) after the eruption. Red solid and broken lines show hot liquid and vapor flows, respectively. Blue solid lines show cold meteoric water flows.**

The block layout of the model is shown in Figure 13. The volcanic geothermal reservoir with higher permeability (500m x 500m x 2000m) is in the central part of the volcano. The natural state model was constructed to fit the rates of discharged water (steam and hot water) and heat, ratio of steam and hot water discharged at the surface and fumarolic temperatures. The good fit model is shown in Figure 14(a). The bottom temperature of the volcanic geothermal reservoir is higher than 500 degree C. The supply rate of magmatic fluids is 45kg/s of which enthalpy is 3500kJ/kg. Most of the volcanic geothermal reservoir is in two-phase and only the central part (100m x 100m x 2000m) of the volcanic geothermal reservoir (500m x 500m x 2000m) is in the superheated state. Fluid flow patterns in the central blocks in the west-east direction are shown in Figure 14(b).

Based on the above-mentioned natural state model, we tried to construct a post eruption model by extracting geothermal fluids of which rates are equal to the observed discharged rates. The geothermal fluids were extracted uniformly from the central part of the volcanic geothermal reservoir (100m x 100m x 2000m). The calculated temperatures eight years after the eruption were shown in Figure 15(a). We can see the temperature decrease in the volcanic geothermal reservoir after the eruption by comparing with the natural state model. The lower part of the reservoir became liquid and part of the superheated steam in the central part disappeared. The mean temperature decrease in the volcanic geothermal reservoir was estimated at about 30 degree C. This is a little smaller compared with the observed fumarolic temperatures or estimated temperature decrease by the geomagnetic analysis. In order to fit the calculated value with observed value much more, we need to modify the shallow permeability structure. At present, we have no data about the detailed permeability structures of the volcanic geothermal reservoir. We will try to modify the permeability structure by applying geophysical exploration in the near future.

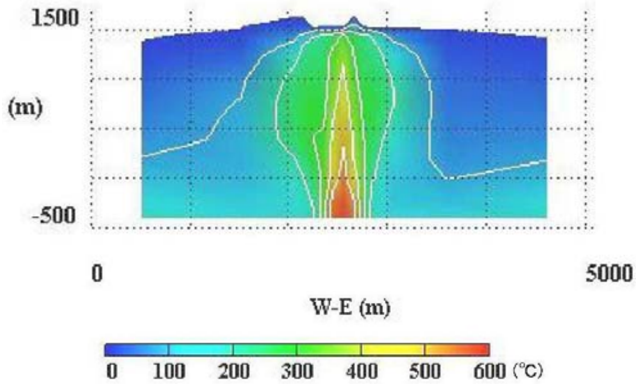



(a)

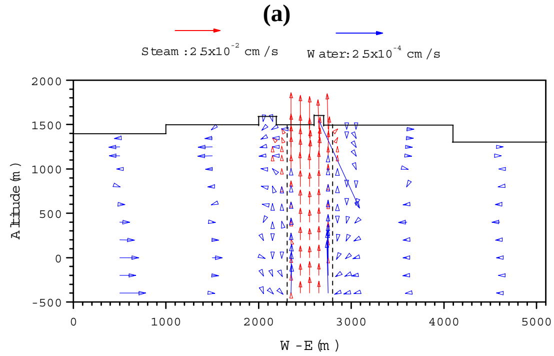



(b)

**Figure 13: Block layout of the model. (a) Plan view, (b) Vertical section.. The red part shows the volcanic geothermal reservoir.**

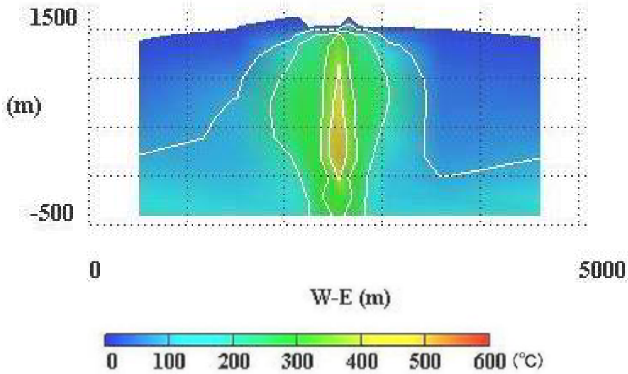



(a)




(b)

**Figure 14: Temperature distribution (a) and fluid flow pattern (b) of the natural state model before the eruption.**

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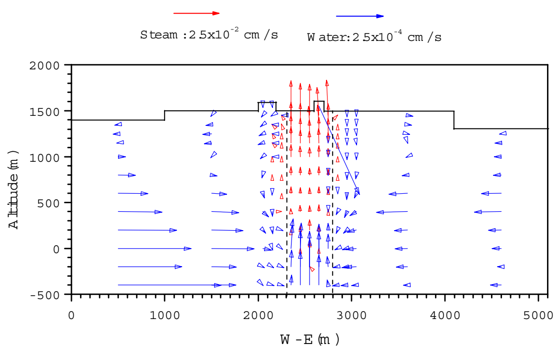


(b)

**Figure 15: Temperature distribution (a) and fluid flow pattern (b) of the post eruption model.**

## 6. CONCLUSIONS

Quick cooling of the volcanic geothermal reservoir beneath Kuju volcano was observed after the 1995 phreatic eruption by repeat geophysical measurements such as thermal, gravimetrical and geomagnetic techniques. It is explained that such quick cooling was caused by the increased cold meteoric groundwater recharge to the volcanic geothermal reservoir accompanied by the sudden decrease in pressure in the volcanic geothermal reservoir by the phreatic eruption. Such a process is very similar to the production of fluid from the geothermal reservoir without reinjection.

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