Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

HEAT AND MASS TRANSFER PROCESSES AFTER 1995 PHREATIC ERUPTION OF KUJU VOLCANO, CENTRAL KYUSHU, JAPAN

Sachio Ehara[1],Yasuhiro Fujimitsu[1], Jun Nishijima[1],Akira Ono[1] and Yuichi Nakano[1]
[1]Laboratory of Geothermics, Kyushu University, Fukuoka 812-8581,Japan

Key Words: hydrothermal system, phreatic eruption, heat discharge rate ,water balance, volcano energy

ABSTRACT

Kuju volcano in central Kyushu, Japan began to erupt on 11 October,1995. The eruption was phreatic in nature, as there was no magmatic activity at the surface even though the vesiculated glass shards were detected from the ash. The heat discharge rate from the fumarolic field of Kuju volcano was about 100MW before the eruption. The heat discharge rate from new craters became higher than 2000MW during about two months after the eruption and subsequently decreased. However, it remained as high as several hundred MW several years after the eruption. We conducted dense repeated thermal and gravity measurements around the new craters in the interval of one week to several months following the eruption. As a result, we detected various thermal and hydrologic changes associated with the new craters and the pre-existing fumaroles. We also clarified that the rate of the groundwater vaporization by the uprising hot magmatic gas is gradually becoming equal to the rate of the water recharge from the surrounding regions, on the basis of the water mass balance determined from the repeat gravity measurements and estimates of the discharged volcanic steam rate. The water mass balance shows that the volcanic activity is gradually approaching a new stable state. These results show that the joint measurement of repeat gravity and water mass discharge rate is a very useful technique to clarify subsurface hydrological processes beneath volcanoes. This method will be also very effective in monitoring the underground hydrological processes when we extract heat from active volcanoes in the future.

1. INTRODUCTION

Thermal energy that is stored beneath active volcanoes (volcano energy) may have an important role in geothermal energy development in the near future. For this purpose, it is important to monitor and clarify the thermal and hydrologic processes occurring beneath volcanoes. Recently, we have been conducting a project to study these processes and to examine the technique for extraction of heat from Kuju volcano in central Kyushu, Japan (Ehara,1992, Ehara and Morita,1995).

Kuju volcano began to erupt on October 11,1995 at the eastern flank of Mt. Hossho, which is in the central part of Kuju volcano. The volcanic steam discharge rate from the new craters and the pre-existing fumarolic fields is still large even three years after the first eruption, although the proposed new magma at shallow depths has not appeared at the surface. Continued monitoring of volcanic activity, mainly in terms of measuring rates of heat and mass transfer, has demonstrated that such measurements provide very effective technique for monitoring the associated hydrological processes. Such processes could result in future phreatic eruptions, which are similar in their effects to production without reinjection of geothermal fluids .

2. KUJU VOLCANO and ITS 1995 ERUPTION

Kuju volcano, composed of many lava domes, is situated in central Kyushu, Japan(Fig.1). It is a typical andesitic island-arc volcano. The main rock type is hornblende andesite. The volcanic activity started about 0.3Ma (Watanabe et al.,1987,Kamata,1996). In historic times, only phreatic eruptions have occurred, at intervals of several tens to one hundred years. An active fumarolic field in the central part of the volcano shows the most intense geothermal activity in the whole of Kyushu Island. The natural heat discharge rate was estimated at about 100 MW before the eruption (Ehara,1992). Temperatures of fumaroles generally exceed 200 degree C and the maximum observed temperature was 508 degree C before the eruption (Mizutani et al.,1986).

A thermal model for Kuju volcano prior to its latest eruptions was developed from geological, geophysical and geochemical data (Ehara,1994), as shown in Fig.2. Magmatic fluids discharged from the cooling magma body rise upward through fractures in the basement rocks and mix with the meteoric water at depths of about 2km depth. This yields two-phase fluid in a reservoir hosted by volcanic rocks between the surface and 2km depth.

Kuju volcano began to erupt on 11 October,1995 from the new craters about 300m south of the pre-existing fumarolic field. The volume of the erupted ash derived from non-juvenile material was about 20000m^3. It erupted again in the middle of December, 1995, producing an ash volume of about 5000m^3. Following these eruptions, rates of heat and steam discharge from the new craters and the pre-existing fumarolic fields increased dramatically and are still above pre-eruptive levels. The 1995 eruptions were phreatic, since there was magmatic juvenile magma produced at the land surface, although vesiculated glass shards were detected in the ash (Hatae et al.,1997).

3. THERMAL AND GRAVITY MEASUREMENTS AFTER 1995 ERUPTION

We started heat and mass discharge measurements shortly following the October 1995 eruption. The thermal measurements include temperature measurements by remote and direct methods and heat discharge rate measurements by remote observation of volcanic steam. Net mass changes were estimated by repeat gravity measurements. The location of the new craters and the pre-existing fumaroles are shown in Fig.3. A, B, and C-regions are the pre-existing fumarolic fields and D- region is a new crater zone. Thermal measurement points are distributed in and around the new craters and the pre-existing fumarolic fields. The solid circles in Fig.3 show gravity stations.

3.1 Thermal Measurements

The temperatures of the new craters and the pre-existing fumarolic fields were monitored by a thermal imagery apparatus and an infrared radiation thermometer. The maximum temperatures obtained by the two different methods showed almost similar patterns of temporal change. The representative patterns of temperature change at different sites are shown in Fig.4. The "B2a" pattern shows the temperatures at a pre-existing fumarole that were observed by the infrared radiation thermometer placed about 1m distant from the target. The temperature decreased gradually just after the first eruption. However, it did not change after the second eruption., and began to increase gradually after the summer of 1997 (Ehara et al., 1997).

The "C" pattern shows the temperatures at a pre-existing fumarole that had been showing the maximum temperature in the central part of Kuju volcano before the eruption. It was also observed about 1m distant from the target. It was 508 degree C in 1960 and decreased to about 350 degree C in 1970s. After that it began to increase up to 402 degree C in 1992. However, it decreased rapidly just after the first eruption and dropped below 100 degree C about two years after the first eruption. Although its temperature was clearly affected by the first eruption, no changes were observed directly after the second eruption. The "d" pattern shows the temperature of the strongest crater in the newly opened craters. It was observed about 300m distant from the target. The temperature measured from that distance is lower than the actual temperature of the discharged gas. However, the discharged gas temperature was not higher than 300 degree C, since that temperature was observed from a distance of about 30m from the crater). The crater temperature increased rapidly just after the first eruption but decreased rapidly just after the second eruption. Then it began to increase again gradually. The patterns of temperature change of "d" and "B2a" were very similar other after the summer of 1997. This suggests that the paths of uprising magmatic gases for the pre-existing fumarolic field and for the new craters may have combined about two years after the eruption.

The heat and steam discharge rates from the new craters and the pre-existing fumaroles were estimated by the remote sensing technique developed by Jinguuji and Ehara(1997). Heat discharge rates are shown in Fig. 5. The rate from "d" crater (solid circles in Fig.5) two months after the first eruption was higher than 2000 MW. It decreased rapidly just after the second eruption. After that it decreased and then recovered slightly. However, after the second eruption the heat discharge rate from the pre-existing fumaroles (diamonds in Fig.5) became larger and larger. Then the total heat discharge from the new craters and the pre-existing fumaroles did not decrease so much. The present total heat discharge rate is several hundred MW which is still several times higher than that discharged before the eruption.

3.2 Gravity Measurements

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 using the SCINTREX CG-3 and CG-3M gravimeters. Observation points for gravity are shown in Fig. 3. Values at all the gravity stations around new craters decreased rapidly during two months after the first eruption and thereafter gradually decreased. The ground around the new craters subsided at a rate of several cm/year after the eruption. Therefore we corrected the effect of height change on gravity. Two examples of gravity change around the new craters are shown in Fig. 6. Patterns of gravity change for different periods are shown in Fig. 7. Application of Gauss's potential theorem to the maps of gravity change yields estimates of 55,000 tons/day and 2,800 tons/day for the average daily mass decrease during the mid-October 1995 to January 1996 period and the January 1996 to November 1998 period, respectively. This indicates that deficiencies in the mass of groundwater beneath the new craters are gradually being eliminated.

3.3 Seismic Activity and Ground Deformation

Shallow microseismic activity beneath the fumarolic field was detected before the eruption when the mean daily frequency of microearthquakes was 3-10 (Ehara,1992). The seismic activity after the eruption has been basically same as that before the eruption, even though the new craters opened about 300m south of the pre-existing fumarolic field (Sudo et al.,1998). Ground deformation measurements show that only subsidence occurred after the eruption (Sudo et al.,1998). Thus, neither seismic observations nor ground movement measurements show the possibility of magma uprising after the eruption.

4. HEAT AND MASS BALANCE BENEATH KUJU VOLCANO

Water mass balances can be calculated by combining the results of the measured steam discharge rates and net mass changes from the new craters and the pre-existing fumaroles. Assuming that the discharged steam from the new craters and the pre-existing fumaroles is derived from a combination of magmatic and meteoric sources, then some groundwater of meteoric origin is being vaporized by rising magmatic water and gas. This implies that recharging groundwater is flowing toward the new crater zones. The percentages of magmatic water and meteoric water in the steam discharging from the new craters is estimated by geochemical means to be about 35% and 65%, respectively, both before and after the 1995 eruptions (Hirabayashi et al., 1996). Such processes are shown quantitatively for different periods (mid-October 1995 to January,1996 and January 1996 to November 1998) in Fig. 8. The rate of groundwater vaporization was very large (~58,000 tons/day) and the rate of groundwater recharge was small (~3,000 tons/day) during two months after the first eruption. Therefore, there was a large net mass loss at the early stage of the eruption. Thereafter, rate of groundwater vaporization became smaller (~17,000 tons/day) and the rate of groundwater recharge became larger (~14,200 tons/day). These results show that the hydrologic system around the new craters is approaching a new equilibrium state. As mentioned above, seismic activity did not change before and after the eruption and ground deformation shows only subsidence after the eruption. However, the discharged steam rate estimated by the remote sensing method and the net mass loss obtained by repeat gravity measurements changed very much before and after the eruption. In such situations (no change of seismic activity and large changes in the heat and water mass balances), monitoring of volcanic activity by heat and water mass measurements is much more effective in clarifying the underground hydrological processes.

5. CONCLUSIONS

Heat and water mass discharge measurements were conducted after the 1995 phreatic eruption of Kuju volcano, central Kyushu, Japan. Based on the water balances, significant changes in the hydrologic system occurred soon after the first eruption, but the hydrologic system has since reached a new equilibrium state. In contrast, seismic activity did not change through the same period. Thus, heat and mass transfer measurements should be considered to be very effective tools in monitoring hydrological processes beneath volcanoes.

REFERENCES

Ehara, S.(1992).Thermal structure beneath Kuju volcano, central Kyushu, Japan. *J. Volcanol. Geotherm. Res.*, Vol.54, pp.107-115.

Ehara, S.(1994).Magmatic hydrothermal system developing just above a cooling magma-A case study of Kuju volcano, central Kyushu,Japan-,*Mem.Geol.Soc.Japan*,No.43,pp.169-177.in Japanese with English abstract.

Ehara, S. and Morita,K.(1995).Thermal structure of Kuju volcano, central Kyushu, Japan and an estimation of the heat extraction rate from the volcanic geothermal reservoir. *Proc. World Geothermal Congress 1995*,pp.1955-1958.

Ehara, S.(1998).1995 Eruption of Kuju volcano and its recent activities. *J. Balneological Soc. Japan*, Vol.48,No.3,pp.72-833. In Japanese with English abstract.

Hatae, K., Watanabe, K., Watanabe, K. Tsutui T., and Motomura,K.(1997).Variation in content of vesiculated glasses in volcanic ash erupted from Kuju volcano in 1995-1996, Japan. *J. Volcanological Soc. Japan*,Vol.42,pp.345-353. In Japanese with English abstract.

Hirabayashi, J., Ohba, T. and Nogami, K.(1996). *Geochemical study associated with the 1995 eruption of Kuju volcano, Kyushu, Japan*. Report for Monbusho Research Project Grant-in-Aid for Development Scientific Research (No.07300017), pp.63-73. In Japanese.

Jinnguuji, M. and Ehara, S.(1997).Estimation of steam and heat discharge rate from volcanoes using maximum diameter of volcanic steam. *J.Volcanol.Soc.Japan*,Vol.41, pp.23-29. In Japanese with English abstract.

Kamata, H.(1997). *Geology of the Miyanohara District*. With Geological Sheet Map at 1:50000,. Geol.Surv.Japan,127pp.in Japanese with English abstract.

Sudo y., Ono, H., Hurst, A. W., Tsutui, T., Mori,T., Nakaboh,M., Matsumoto,Y., Sako,M., Yoshikawa,S., Tanaka, M., Kobayashi, Y., Hashimoto, T., Hoka, T., Yamada, T., Masuda, H., and Kikuchi, S.(1998). Seismic activity and ground deformation associated with 1995 phreatic eruption of Kuju volcano, Kyushu, Japan. *J. Volcanol. Geotherm. Res.*, Vol.81, pp.245-267.

Watanabe, K., Hayashi, M. and Fujino, T.(1987).Fission track age of volcanoes in the Kuju volcanic region in relation to geothermal activity. *J. Geothermal Res. Soc. Japan*, Vol.9, pp.207-217.

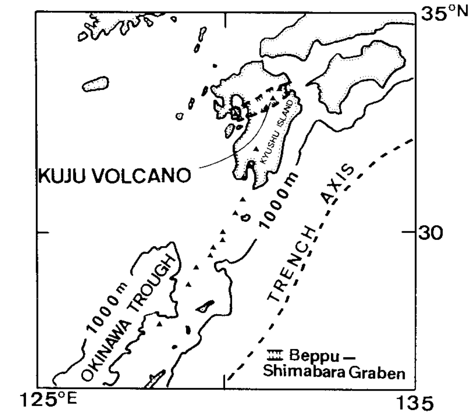

Figure 1. Location map of Kuju volcano, Kyushu, Japan.

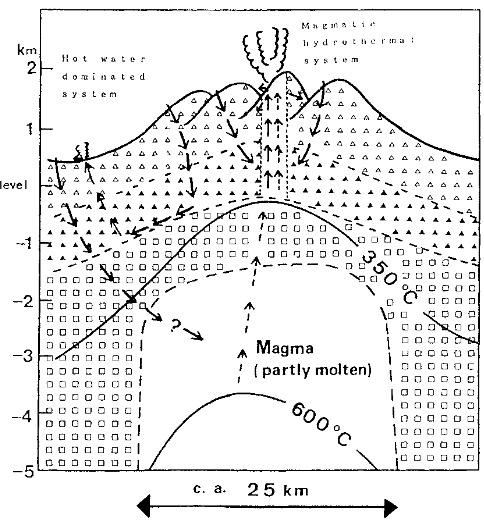

Figure 2. Thermal model of Kuju volcano. Triangles and open rectangles show volcanic rocks and granitic basement rocks, respectively. Solid and broken arrows indicate flow pattern of liquid and vapor water, respectively.

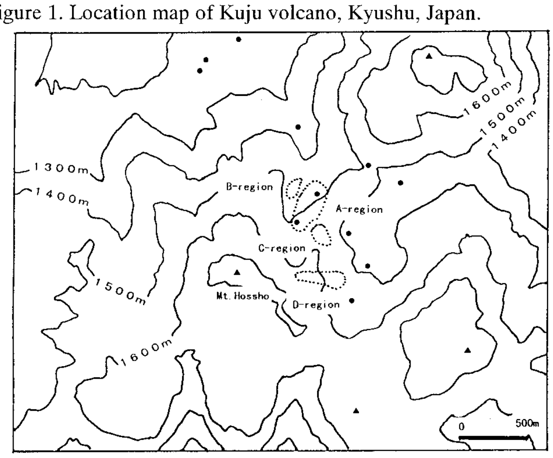

Figure 3. Map of the central part of Kuju volcano. A,B, and C-regions are the pre-existing fumarolic fields. D-region is a new crater zone. Solid circles show the stations for the repeat gravity measurements.

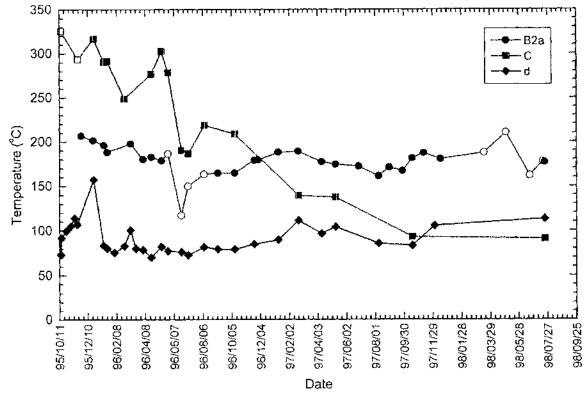

Figure 4. Representative patterns of temperature change at a new crater(d) and pre-existing fumaroles(B2a and C).

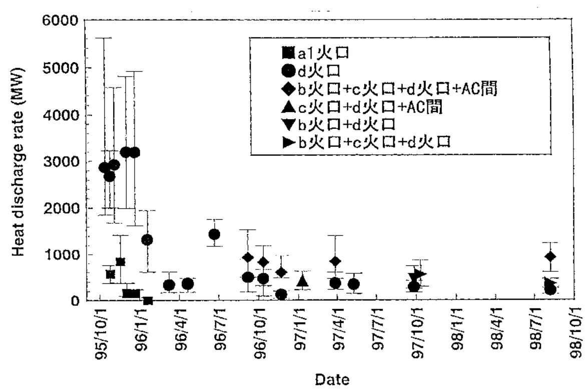

Figure 5. Temporal variations of heat discharge rates from the new craters and the pre-existing fumaroles. Solid diamonds and triangles include the heat discharge rates from the new craters and the pre-existing fumaroles. Other symbols include the heat discharge rates from only the new craters.

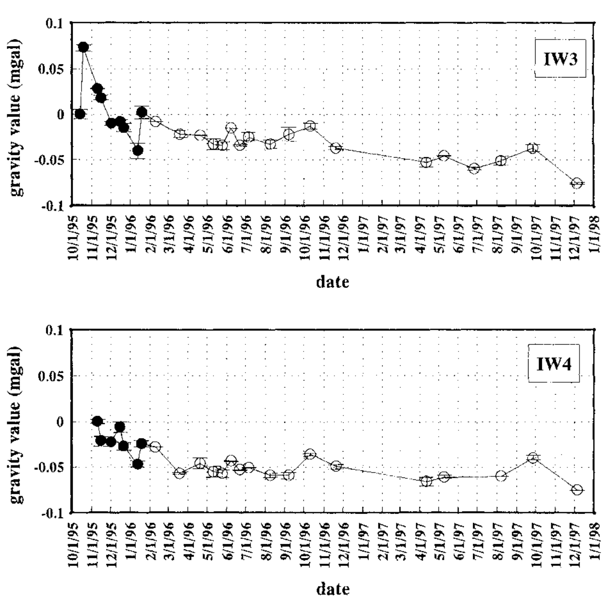

Figure 6. Two examples of gravity change around the new craters. The solid and open circles show the observed values by the Scintrex CG-3 and CG-3M gravimeters, respectively.

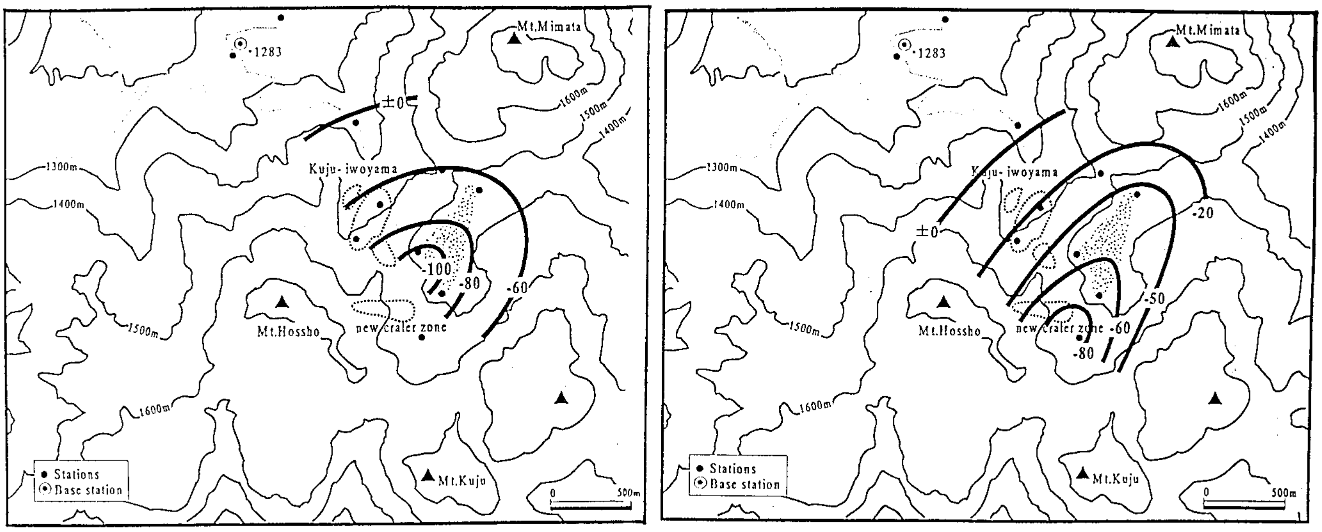

Figure 7. Patterns of gravity change at the new craters. Left: from mid-Oct.,1995 to January,1996, Right: from January, 1996 to November,1998.

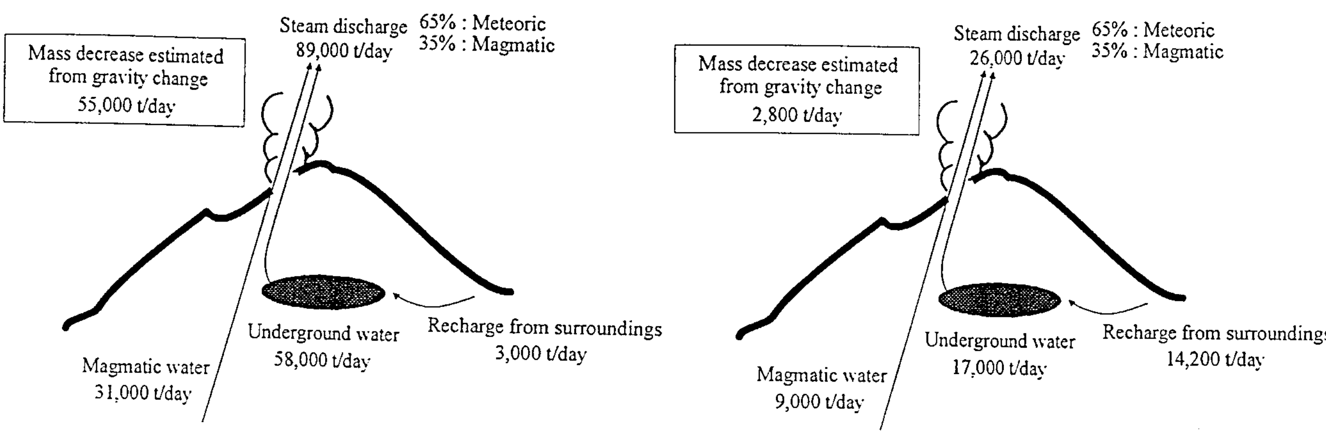

Figure 8. Changes in hydrological system after the eruption, estimated by changes in gravity and volcanic steam discharge rate. Left: from mid-Oct.,1995 to January,1996, Right: from January,1996 to November,1998.