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Transition of Numerical Models for the Hydrothermal System of the Kuju Volcano, Japan

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ABSTRACT

The Laboratory of Geothermics, Kyushu University, has been conducting researches on the Kuju Volcano in Kyushu Island, Japan, for the research of future volcanic energy utilization since the 1970s. Furthermore, some numerical models of the thermal structure and hydrothermal system of the Kuju Volcano have been constructed in order to integrate the obtained research results at each step since the late 1980s.

The broad area model in the 1990s was a 2-D transient thermal conduction model of a vertical N-S section that had an extension of 50 km. The model showed that the present heat flow distribution of the Kuju Volcano estimated by five deep geothermal wells is explained by a cooling magma that had been emplaced 50,000 years ago. And the local area model, which was a cylindrical coordinates geothermal fluid flow model that had a diameter of 5 km centered on Kuju Iwoyama, the solfatara field of Kuju Volcano, concluded that a concentration zone of microearthquake hypocenters (a cylindrical zone of about 500 m in diameter and 2 km height beneath the solfatara field) is a two-phase permeable zone (a volcanic geothermal reservoir).

When the 1995 phreatic eruption occurred at Kuju Iwoyama, we constructed a 3-D transient geothermal fluid flow model, which had the horizontal extension of 5.1 km (N-S) by 5.1 km (E-W) and covered from the ground surface to -500 m asl, as a local area model to explain the temporal changes of the heat discharge rate by the fumarolic activity and of the average volcanic geothermal reservoir temperature estimated by the geomagnetic observation. In recent, we are trying to improve the 3-D local area model to explain the gravity change observed during the volcanic activity period of the 1995 eruption. Moreover, we are also conducting a 3-D transient geothermal fluid flow model, which has the horizontal extension of 49 km (NW-SE) by 39 km (NE-SW) and vertically covers from the ground surface to -10 km asl, as a broad area model to explain the development of the hydrothermal systems in the Kuju Volcanic Area including some geothermal power station regions.

1. INTRODUCTION

The Kuju Volcano is located in southwestern part of Oita prefecture in Kyushu Island, southwestern Japan (Figure 1), and is one of the most eminent geothermal areas in Japan, in which 3 commercial (Otake, Hatchobaru Nos. 1 & 2 and Takigami) and 1 private (Kuju) geothermal power stations are in operation. This volcano mainly consists of more than twenty andesitic domes (Kamata, 1997) with high terrestrial heat flow of over 100 mW/m^2 (Ehara, 1992) (Figure 1).

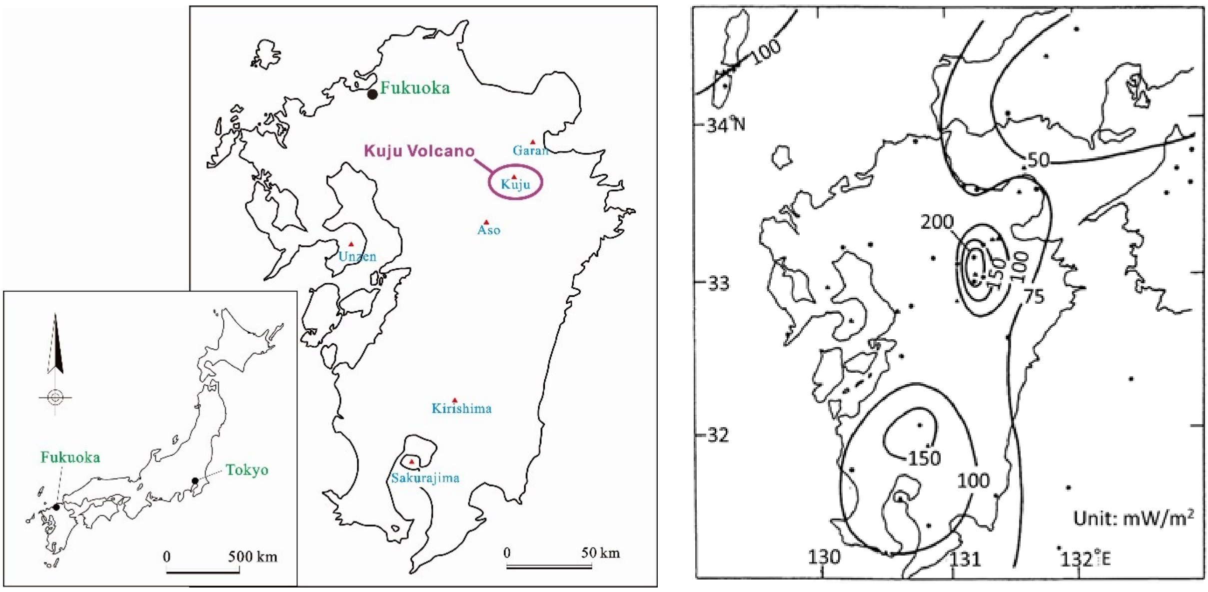


Figure 1: Location of Kuju Volcano (left), and the terrestrial heat flow distribution of the Kyushu district in Japan (Ehara, 1992) (right).

The volcanic activity started about 200 ka, and the most recent lava dome (Kurodake) appeared about 1600 years ago (Kawanabe et al., 2015). In historical times, only phreatic eruptions have occurred at an interval of about a hundred years. The 1995 phreatic eruption, the most recent phreatic eruption occurred in October and December 1995, created new craters about 300 m south of Kuju Iwoyama (the pre-existing solfatara field of Kuju Volcano). The fumarolic activity of the new craters completely stopped in 2003, but the activity of Kuju Iwoyama continues.

The Laboratory of Geothermics, Kyushu University, has been conducting researches of the Kuju Volcano for the research of future volcanic energy utilization since the 1970s. Some numerical models of the thermal structure and hydrothermal system of the Kuju Volcano have been constructed in order to integrate the obtained research results at each step since the late 1980s.

2. NUMERICAL MODELING OF KUJU VOLCANO

From the early stage of the numerical modeling of the Kuju Volcano in our laboratory, two types of models, namely broad area models that cover the whole of the Kuju Volcanic Area and local area models around Kuju Iwoyama were already constructed, and this modeling policy has continued until now.

2.1 Numerical models from the late 1980s to the 1990s

Ehara (1992) estimated the present heat flow distribution of the broad area, including Kuju Volcano by using the heat flow data of 5 deep geothermal wells (Figure 2) and constructed a 2-D transient thermal conduction model by using a computer program FINITEG (Lee et al., 1980). The model was a vertical N-S section that had a horizontal extension of 50 km and a vertical extension from the ground surface to -10 km asl and consisted of 4 layers with different properties (Figure 2, Table 1). Based on the volcanic history, a magma of 1,000°C was emplaced 50,000 years ago for the initial condition (Figure 3). The most suitable model showed that the present heat flow distribution of the Kuju Volcano is explained by a cooling magma that had been emplaced 50,000 years ago (Figure 3).

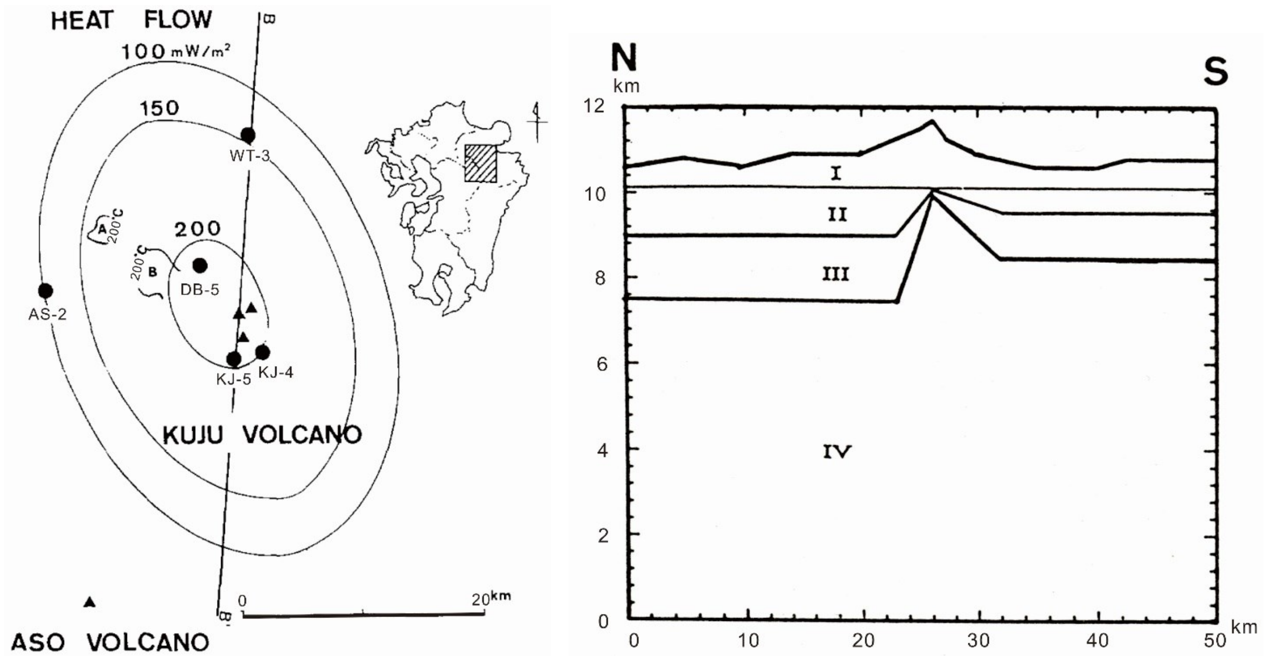


Figure 2: Terrestrial heat flow distribution of the broad area, including Kuju Volcano. Solid circles indicate the deep geothermal wells (left). And a 2-D vertical N-S section of the transient thermal conduction model (right). A black line in the left figure indicates the location of the vertical section (Ehara, 1992).

Table 1: Physical properties of each layer in the right figure of Figure 2 for the most suitable model (Ehara, 1992).

	Thermal diffusivity[1] $(10^{-6} m^2/s)$	Thermal conductivity[2] (W/mK)	Density[2] (kg/m^3)	Specific heat[3] (J/kg K)	Radioactive heat production[3] $(10^{-6} W/m^3)$
Layer I	0.7	1.3	2350	800	3.0
Layer II	0.8	1.3	2140	800	3.0
Layer III	0.9	1.5	2120	800	3.0
Layer IV	0.9	1.9	2640	800	3.0

[1] calculated parameter (=Thermal conductivity/(Density * Specific heat))
[2] measured values (NEDO, 1988)
[3] assumed values (Buntebarth, 1984)

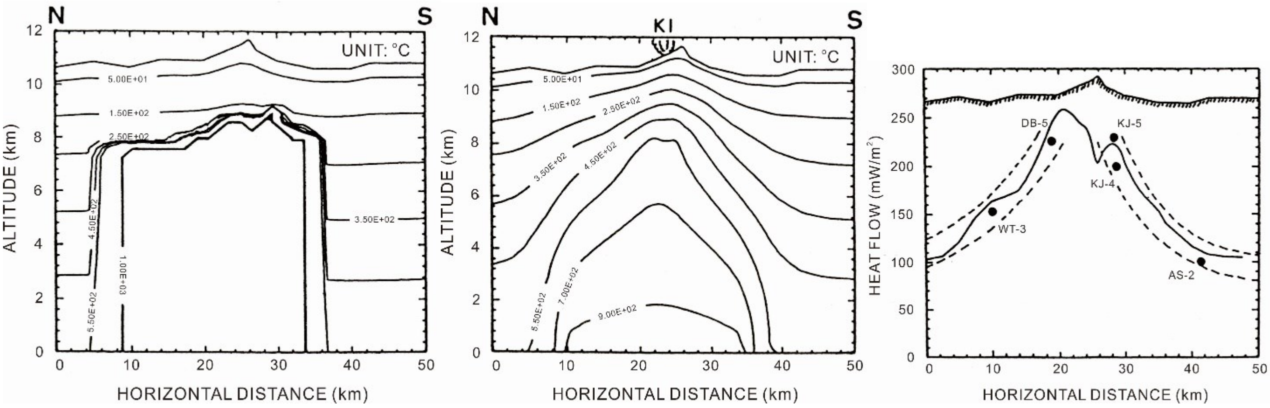


Figure 3: Initial (left) and the present (50,000 years after the emplacement of the magma, center) temperature distributions of the most suitable model. The isothermal line of 1,000°C in the left figure indicates the shape of the emplaced magma. The right figure shows the comparison of the heat flow distribution between the calculated values from the central figure (a solid curved line) and the estimated values of 5 deep geothermal wells (solid circles) (Ehara, 1992).

The local area model of Kuju Volcano in the 1990s was constructed to explain the reason for the existence of a concentration zone of microearthquake hypocenters. The intensive observation of microearthquake around Kuju Iwoyama was conducted from May to June 1986 (Ehara et al., 1990). As a result, high microearthquake activities were detected, and the hypocenters were concentrated in a cylindrical zone of about 500 m in diameter and 2 km height just beneath the solfatara field (Figure 4).

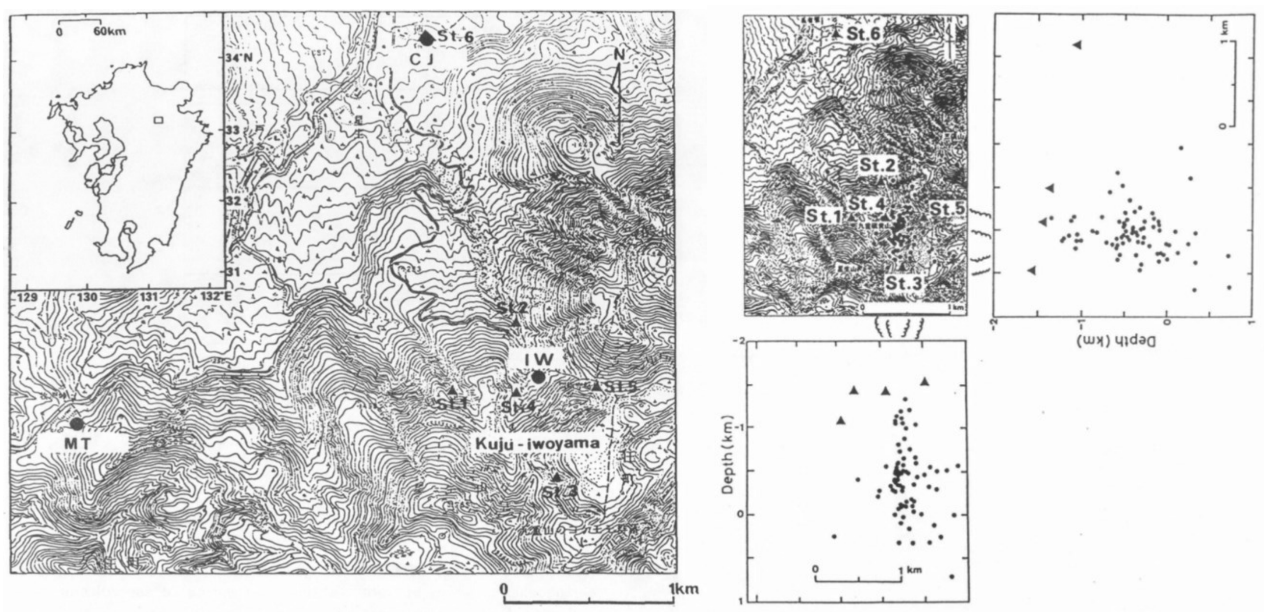


Figure 4: Seismic stations of the multipartite microseismic observation (left). The solid triangles indicate the multipartite seismic stations (St. 1 to 6) and the solid circles indicate the seismic stations for the monitoring (IW, MT and CJ). The right figure shows the hypocenter distribution near Kuju Iwoyama. The solid triangles indicate the multipartite seismic stations and the solid circles indicate the hypocenters (Ehara et al., 1990).

The local model was a cylindrical coordinates geothermal fluid flow model by using a computer program SHAFT79 (Pruess and Schroder, 1980) following the conceptual model (Figure 5). The model had a diameter of 5 km centered on Kuju Iwoyama and a height from the ground surface to the depth of 2 km and consisted of 3 kinds of blocks with different properties (Figure 5, Table 2).

Table 2: Physical properties of each block in the right figure of Figure 5 for the most suitable model (Ehara, 1992).

	Thermal conductivity[1] (W/mK)	Density[1] (kg/m^3)	Porosity[1] (%)	Specific heat[1] (J/kg K)	Permeability[2] (m darcy)
Block A	1.65	2450	17.5	775	50
Blocks B and C	1.80	2500	10.0	775	1

[1]assumed based on the data of NEDO (1988) and Buntebarth (1984).
[2]estimated through preliminary simulations. But they are kept constant in later simulations.

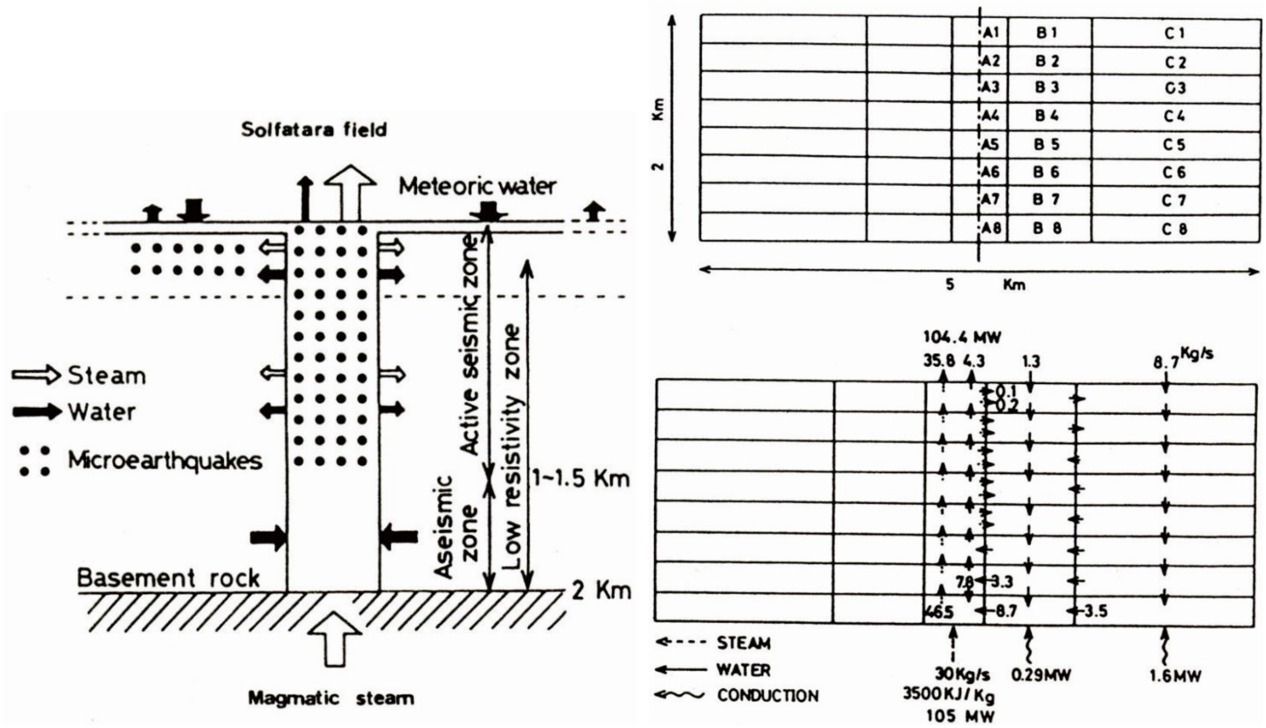


Figure 5: Conceptual thermal model beneath Kuju Iwoyama based on the result of the microearthquake observation (left). The upper right figure shows the block layout of the numerical model. The lower right figure indicates the calculation result (heat and fluid transfer) of the most suitable model (Ehara, 1992).

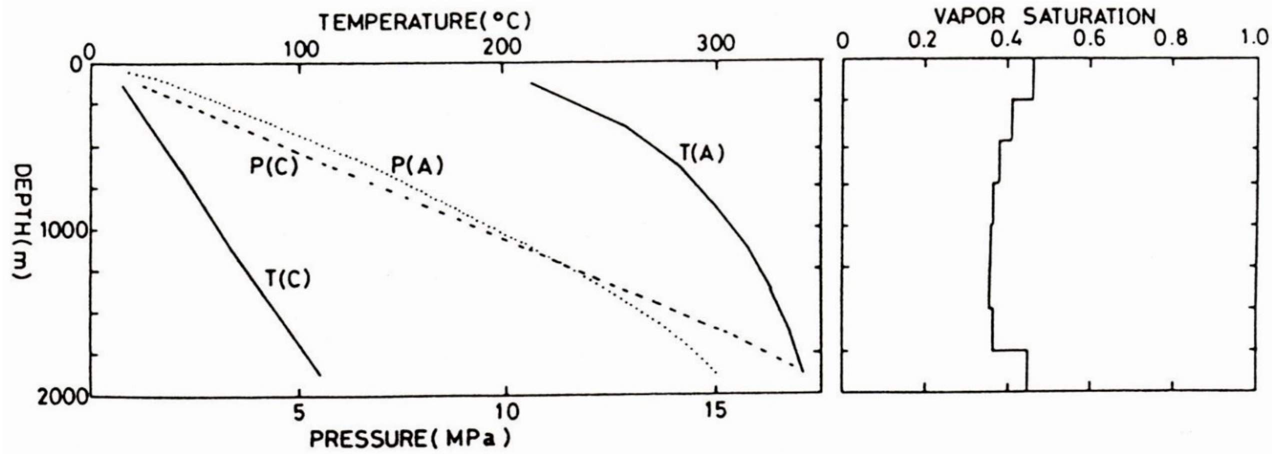


Figure 6: Temperature (T(A) and T(C)) and pressure (P(A) and P(C)) profiles in the blocks A (the central permeable zone) and C (the outside of the central permeable zone) (left), and the vapor saturation profile in the blocks A (right) (Ehara, 1992). See the upper right figure of Figure 5.

The pressure in the central permeable zone P(A) is a little bit (up to 1 MPa) higher than that in the outside of the central permeable zone P(C) (hydrostatic pressure distribution) at the shallower part, and the whole of the central permeable zone is two-phase (Figure 6). Therefore, the higher pressure in the central permeable zone may be the cause of high seismic activity in this zone, since the increase of pore pressure lowers the strength of the rocks (Ehara, 1992).

Therefore, the local area model concluded that the concentration zone of microearthquake hypocenters is a two-phase permeable zone (a volcanic geothermal reservoir).

2.2 Numerical models from the 2000s

When the 1995 phreatic eruption occurred at Kuju Iwoyama, many organizations conducted various observations. A 3-D transient geothermal fluid flow model was created, which had the horizontal extension of 5.1 km (N-S) by 5.1 km (E-W) and covered from the ground surface to -500 m asl, as a local area model (Figure 7) by using a computer program HYDROTHERM Version 2.2 (Hayba and Ingebritsen, 1994) to explain the temporal changes of the heat discharge rate by the fumarolic activity and of the average volcanic geothermal reservoir temperature estimated by the geomagnetic observation.

This numerical model consisted of 3 kinds of rock (Quaternary volcanic rock, a volcanic geothermal reservoir and a conduit), and the properties were assigned to each rock (Table 3). At the ground surface, the temperature and pressure were fixed at 15°C and 1 atm.

The bottom boundary was impermeable, and constant heat flow (200 mW/m^2) was assigned. Furthermore, the hydrostatic pressure and background temperature distribution caused by the constant heat flow were assigned at the lateral boundaries. The activity period of Kuju Iwoyama was divided into 7 stages, and modified the permeability of the conduit and the production rate of the high enthalpy fluid (3,500 kJ/kg) at the high enthalpy fluid source block by trial and error to fit the calculated temporal changes of the heat discharge rate and the average volcanic geothermal reservoir temperature to the observed values (Figure 8). The permeability of the conduit and the production rate of the high enthalpy fluid at each stage of the most suitable model are listed in Table 4.

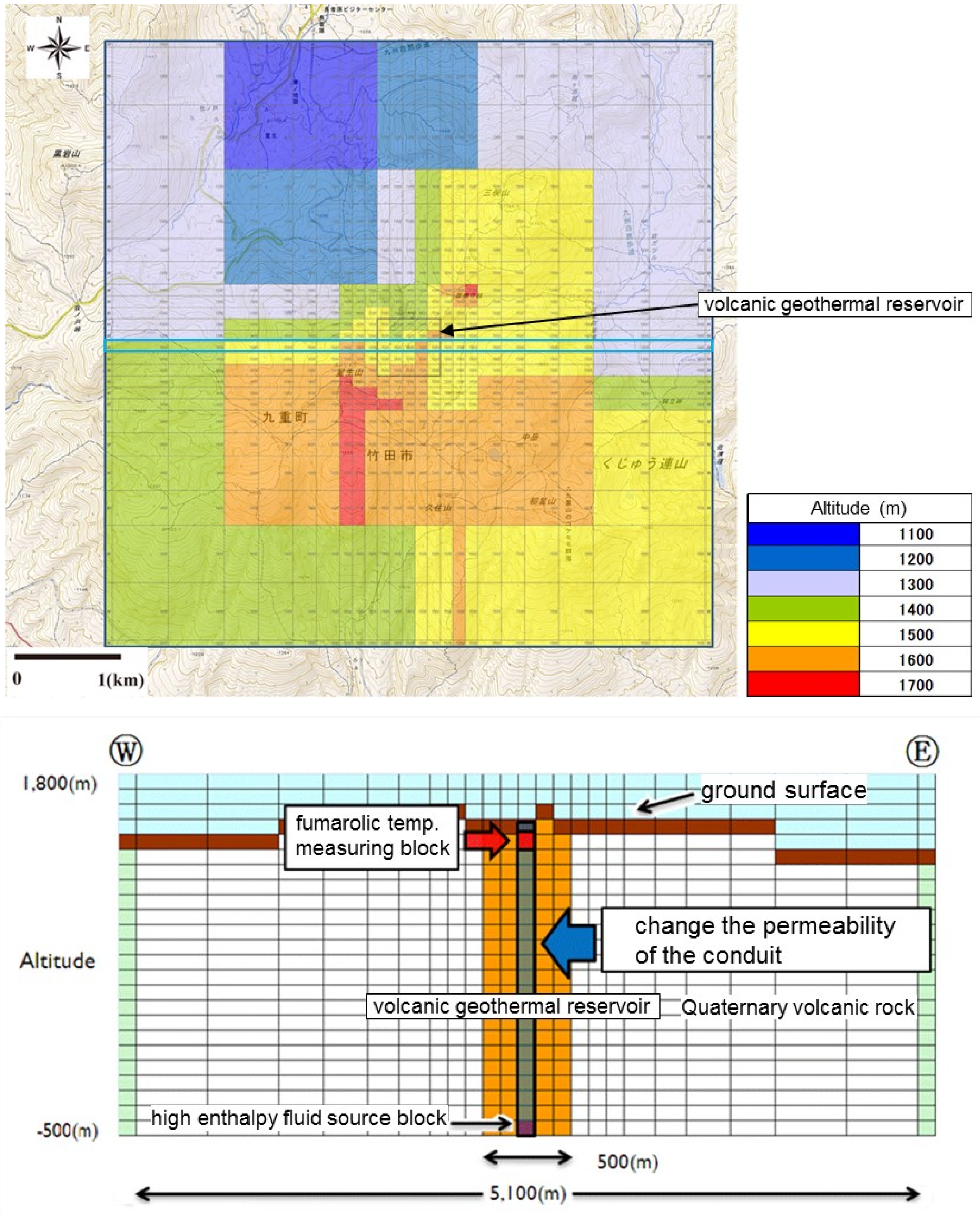
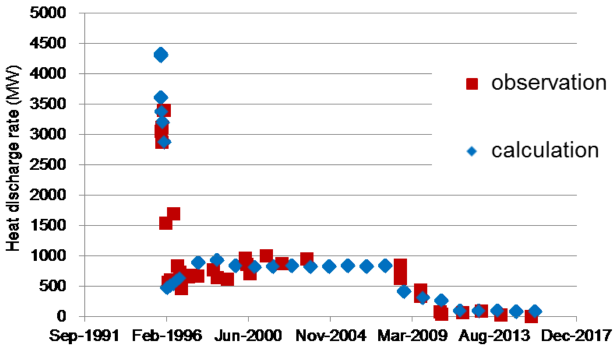


Figure 7: Block layout of a local area (around the Kuju Iwoyama) model. The upper figure displays the horizontal extent with the altitude of the ground surface blocks. The lower figure shows the E-W vertical section that passes through Kuju Iwoyama. A blue rectangle frame in the upper figure indicates the location of this vertical section.

Table 3: Physical properties of each rock in Figure 7 for the most suitable model.

	Quaternary volcanic rock	Volcanic geothermal reservoir
Heat capacity (J/kg K)	775	775
Density (g/cm^3)	2.5	2.45
Porosity (%)	10	17.5
Permeability (mdarcy)	1	50
Thermal conductivity (W/m K)	1.8	1.65



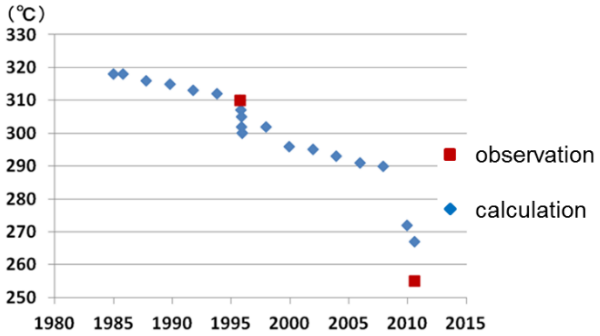


Figure 8: Temporal changes in the heat discharge rate by the fumarolic activity (left) and of the average volcanic geothermal reservoir temperature (right). The observed plots of the average volcanic geothermal reservoir temperature were estimated by the geomagnetic observation.

Table 4: Permeability of the conduit and the production rate of the high enthalpy fluid in Figure 7 for the most suitable model at each activity stage of Kuju Iwoyama.

Activity stage	Permeability (mdarcy)	Production rate of the high enthalpy fluid (kg/s)
(1) Normal activity (for 15,000 years)	50	45
(2) For 10 years before the 1995 eruption	250	45
(3) Just after the 1995 eruption	35000	230
(4) From 2 month to 12 years after the eruption	3500	230
(5) From 12 years to 15 years after the eruption	2500	20
(6) From 15 years to 17 years after the eruption	250	20
(7) From 17 years to 20 years after the eruption	50	20

In recent, we are trying to improve the 3-D local area model to explain the gravity change observed during the volcanic activity period of the 1995 eruption (Figure 9) by using a computer program HYDROTHERM Version 3.2 (Kipp Jr. et al., 2008).

Moreover, we are also conducting a 3-D transient geothermal fluid flow model, which has the horizontal extension of 49 km (NW-SE) by 39 km (NE-SW) (Figure 10) and vertically covers from the ground surface to -10 km asl, as a broad area model to explain the development of the hydrothermal systems in the Kuju Volcanic Area including some geothermal power station regions by using HYDROTHERM Version 2.2 (Fujimitsu et al., 2015). This study area was horizontally divided into 42 blocks in a NE-SW direction and 50 blocks in NW-SE direction (Figure 10) with 38 horizontal layers from 1800 m (top) to -10 km sea level (bottom). The height of each layer is 100 m for the layers above sea level and is 500 m for them below sea level. The calculation conditions for the numerical simulations of the hydrothermal system are shown in Table 5. First, we constructed an initial model that was calculated for 500,000 years with the same boundary conditions as Table 5 without a magma chamber, the faults, the cap rocks and the volcanic conduit in order to obtain the background pressure and temperature distributions. Next, we added the magma chamber, the faults and the cap rocks to the initial model and simulated the hydrothermal system for 50,000 years (Table 5). The volcanic conduit was set in this model after 35,000 years have passed since the simulation was started.

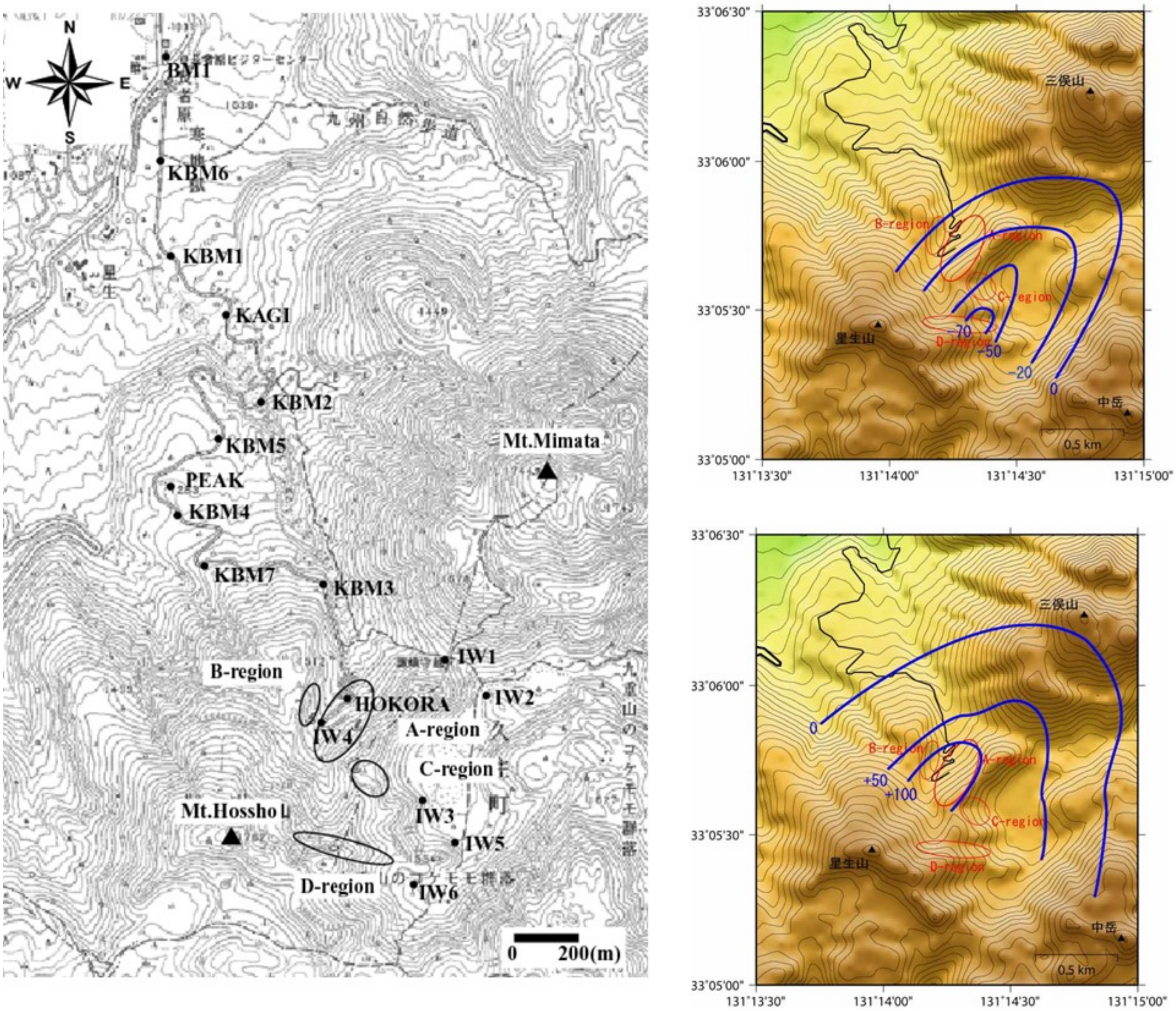


Figure 9: Location of the gravity observation stations (left) and the gravity change observed during the volcanic activity period of the 1995 eruption (right). The observation period of the upper right figure is from January 1996 to December 1997 and that of the lower right figure is from January 1998 to May 2001.

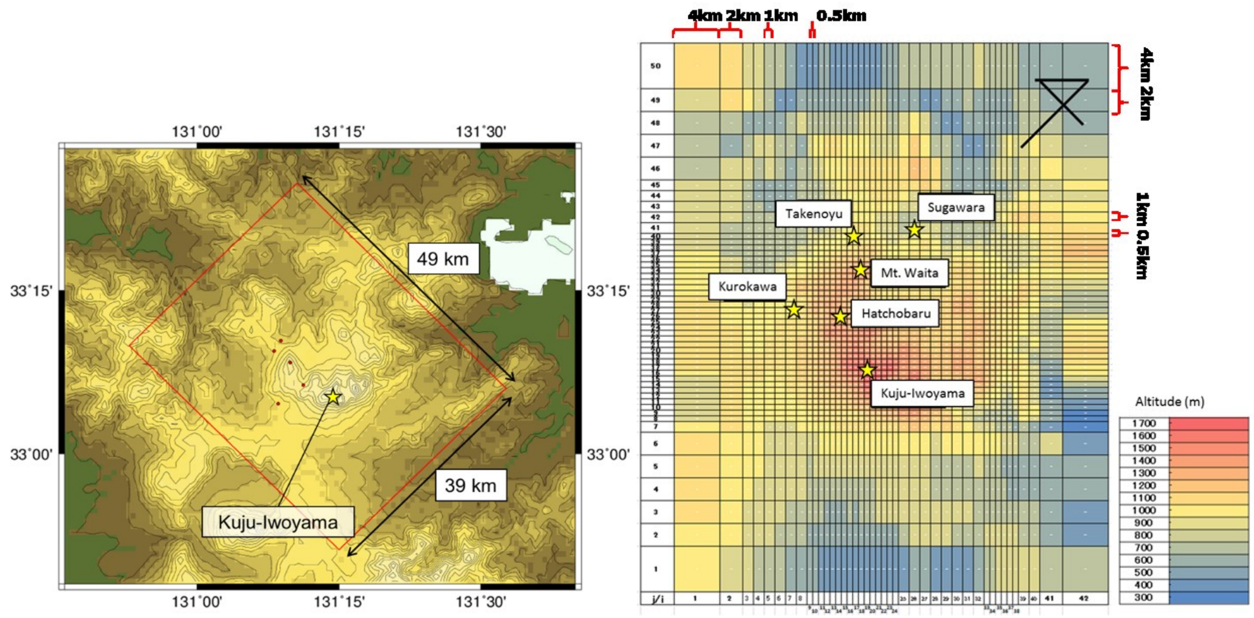


Figure 10: Location of the broad area model (left), and the digitized topographic map of the study area (right).

Table 5: Calculation conditions for numerical modeling (Fujimitsu et al., 2015).

Period of calculation	50,000 years
Top boundary	Ground surface elevation dependence
	15°C at 150 m asl with -0.6°C /100 m (temperature)
	1.013 bar at sea level with -0.01 bar/100 m (pressure)
Lateral boundary	Thermally insulation
	Impermeable
Bottom boundary	Terrestrial heat flow (80 mW/m^2)
	Impermeable
Temperature of magma	1000°C

The simulated results were compared with the observed temperature profiles of the wells to confirm that this model explains the hydrothermal system of the Kuju Volcanic Area. Moreover, the rock properties and the shape of the magma chamber were modified by trial and error to match the calculated and observed temperature profiles.

Figure 11 is an example of the simulation result. According to this numerical model, a vapor dominated zone appears beneath the Hatchobaru area (in a white rectangle frame).

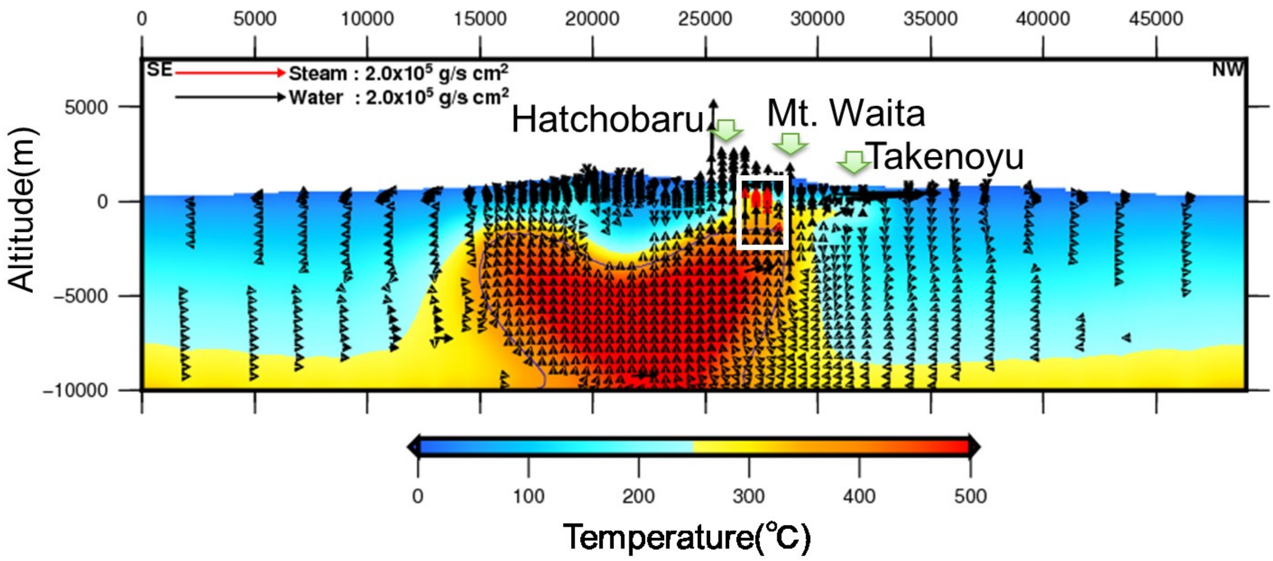


Figure 11: Present temperature and mass flux distributions on the vertical section that passes through the Hatchobaru geothermal power station and the Takenoyu geothermal area.

Both of the broad area model and the local area model with new information are still being improved. In order to decide more precise basement rock depth distribution, we are progressing the airborne gravity gradient data analysis.

3. CONCLUSION

From the early stage of the numerical modeling of the Kuju Volcano, broad area models that cover the whole of the Kuju Volcanic Area and local area models around Kuju Iwoyama were already constructed, and this modeling policy has continued until now. Furthermore, when new events, not only an intensive observation and an eruption but also development of a new computer program for modeling of a geothermal system, occurred, the models were improved based on the new knowledge.

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