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Numerical Modeling of Hydrothermal Systems around Kuju Volcanic Field -An Attempt of Numerical Modeling for a Broad Geothermal System-

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ABSTRACT

We are attempting to construct a numerical model of a broad geothermal system that has the scale of a volcanic field to explain the existence of the hydrothermal systems, which are generated by a heat source like a magma chamber in the volcanic field. And one of the targets is the Kuju volcanic field.

The Kuju volcanic field is located in the southwestern part of Oita prefecture, Japan, and consists of some andesitic volcanoes. There are many hot springs and several geothermal power stations in this field. In the previous studies on the Kuju volcanic field, the numerical models were mainly for the power station areas or the center of Kuju Volcano. So we constructed a new conceptual model that includes the center of the volcano and all of the geothermal power station areas. Based on this conceptual model, we constructed a numerical model that replicates the hydrothermal systems of the geothermal power station areas roughly although the numerical model is not so complicated.

1. INTRODUCTION

One of the research subjects of Laboratory of Geothermics, Department of Earth Resources Engineering, Kyushu University is to construct a numerical model of a broad geothermal system that has the scale of a volcanic field to explain the existence of the hydrothermal systems, which are generated by a heat source like a magma chamber in the volcanic field. In the previous research, we constructed a numerical model of the Unzen volcanic field in Kyushu, Japan, that explained the existence of four geothermal areas in the field by the heat sources estimated by the geodetic explorations before and during the 1990-95 eruption of Unzen Volcano (Fujimitsu et al., 2008). And one of the recent modeling target is the Kuju volcanic field (Figure 1).

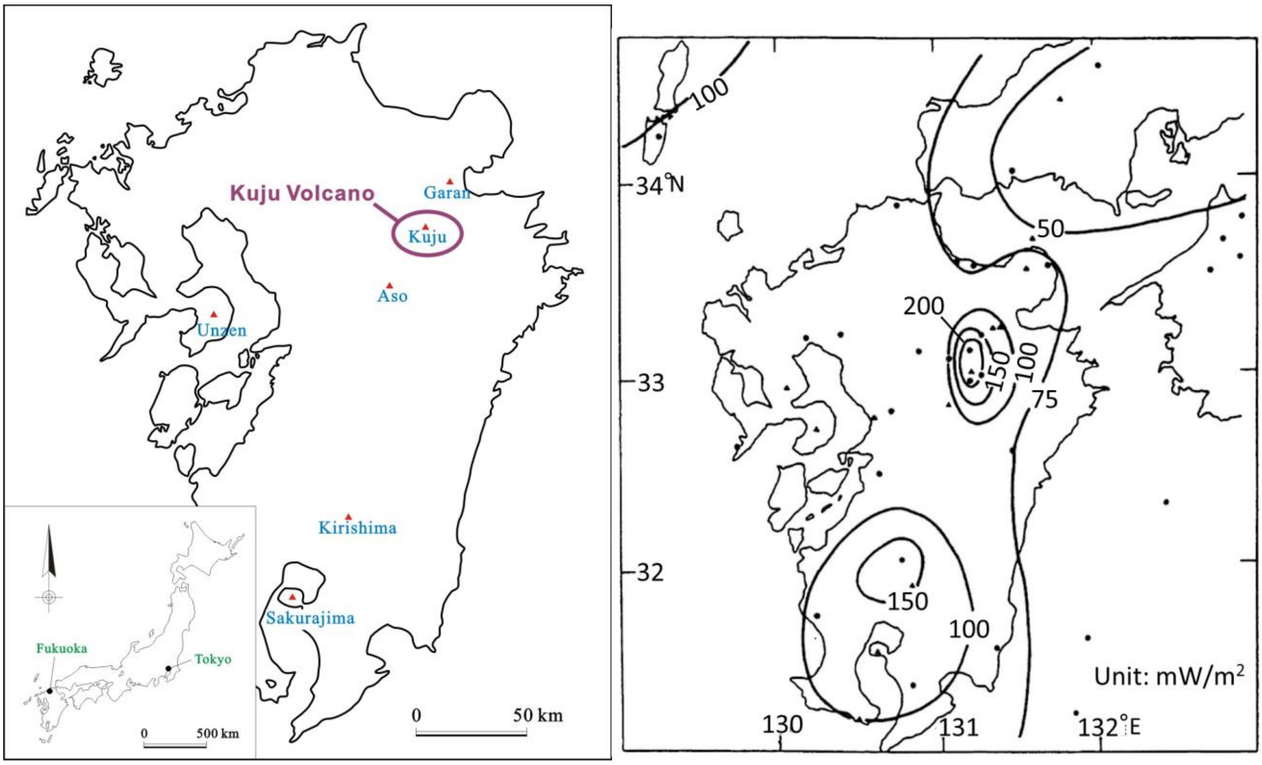

Figure 1: Location of Kuju Volcano (left), and the terrestrial heat flow distribution of the Kyushu district in Japan (Ehara, 1992) (right).

The Kuju volcano field is located in south western part of Oita prefecture, 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 volcanic field 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).

2. PREVIOUS CONCEPTUAL MODEL OF THE KUJU VOLCANIC FIELD

Figure 2 indicates a previous conceptual model of the Kuju volcanic field that was constructed in our laboratory. And our new conceptual model is based on this previous model in this study. A summary of the previous model is shown below.

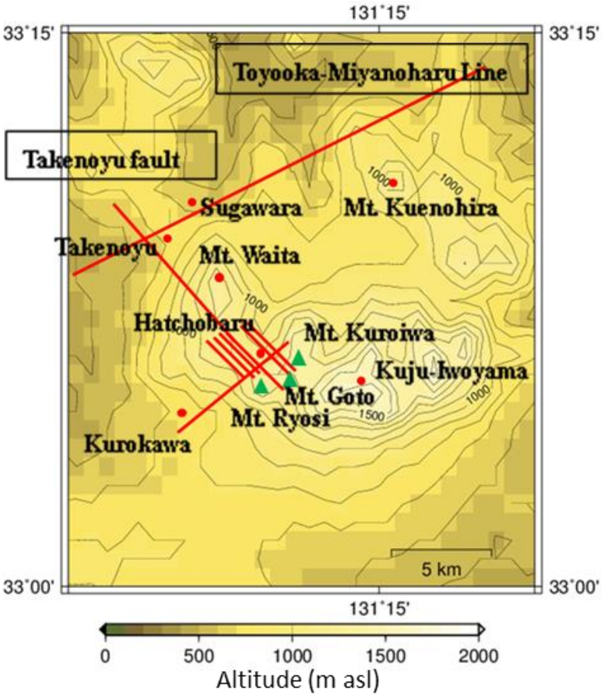

Figure 2: A conceptual model of the Kuju volcanic field (previous model).

2.1 Magma Chamber

Yoshikawa et al. (2005) indicated the three-dimensional seismic velocity structure beneath Kuju Volcano by using the seismic tomography technique with natural earthquakes, and the existence of a magma chamber was inferred. Therefore, we tried to construct a numerical model of this field with one magma chamber.

2.2 Hatchobaru Area

This model is based on the research results of Manabe and Ejima (1984), Kawamura (1985) and Shimada et al. (1994), which explain that the hot water flows into the Hatchobaru area along the NW-SE faults from the Mt. Goto side.

2.3 Takenoyu and Sugawara Areas

According to Yasukawa et al. (1998), the hydrothermal system of the Takenoyu area is formed by hot water from Mt. Waita. Therefore, the hot water flow along Takenoyu Fault was considered in this model. In addition, the Nogami Mudstone layer lies in the northwestern part of Mt. Waita at 500 m above sea level and the thickness is about 100 m (Tamanyu, 1985). However, there is no cap rock right beneath Takenoyu (Yuhara et al., 1983). Therefore, we set the layers of Nogami Mudstone that plays a role of the cap rock of the area except a zone along the Takenoyu Fault.

And in this model, the hot water flows from the Takenoyu area to the Sugawara area by Toyooka-Miyanoharu Line. Toyooka-Miyanoharu Line is a lineament in the direction of NE-SW (Hase et al., 1985).

3. NEW CONCEPTUAL MODEL OF THE KUJU VOLCANIC FIELD

A numerical model based on the previous conceptual model explained the thermal structure of the Kuju volcanic field roughly. However, there were some problems in the previous model. Therefore, we tried to improve the previous conceptual model to solve the problems.

3.1 Problems of the Previous Model

The first problem was the treatment of the NW-SE faults in the Hatchobaru area. In the conceptual model, the hot water flew along the faults. But the previous numerical model could not describe this flow, because the blocks of the numerical model that were assigned as the faults did not possess anisotropy of horizontal permeability.

The second one was about Toyooka-Miyanoharu Line. Kamata (1997) showed some discontinuous faults at the northern part of Mt. Waita instead of the huge Toyooka-Miyanoharu Line (Figure 3). So we adopted the newer research result.

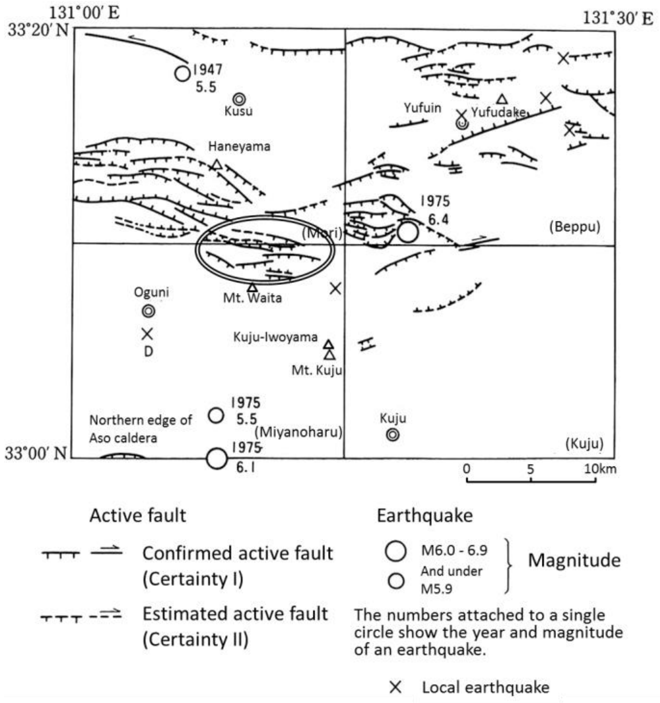

Figure 3: Distribution of active faults around the Miyanoharu area (Kamata, 1997). A double ellipse indicates the location of Toyooka-Miyanoharu Line in Figure 2.

The final one was about the geological structure around Mt. Kuenohira, which is located near the Takigami geothermal power station. Some faults exist around Mt. Kuenohira (Figure 4). However, the previous model did not consider the faults.

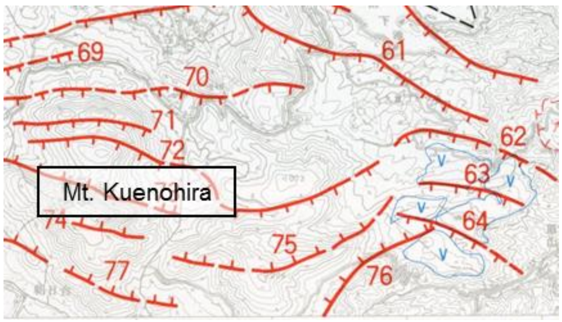

Figure 4: Distribution of active faults around Mt. Kuenohira (The Research Group for Active Tectonics in Kyushu, 1989).

3.2 New Conceptual Model

In order to solve the problems described above, we constructed a new conceptual model (Figure 5).

We replaced Toyooka-Miyanoharu Line with Sibayakata Fault, Amagayaike Fault and Waitanakadake Fault (Kamata, 1997), and set some faults around Mt. Kuenohira with consideration of Figure 4.

The faults at the Hatchobaru area surrounded by a circle in Figure 5 were given anisotropy for expressing the flow from southeast to northwest. And we also aimed at examining the hot water flow from the Hatchoubaru area to the Kurokawa area by setting this anisotropy for the discussion about another origin of the hot water for the Kurokawa area.

4. NUMERICAL MODELING

We adopted HYDROTHERM-Version 2.2 (Hayba and Ingebritsen, 1994) for numerical simulation of hydrothermal system.

The size of our study area for numerical modeling is 49 km in NW-SE direction and 39 km in NE-SW direction (Figure 6). It means that the long side of the rectangular study area is turned counterclockwise 45°. Kuju-Iwoyama, which erupted phreatically in 1995, is about the center of the study area. And the digitized topography with 100 m step is also indicated in Figure 6.

4.1 Division and Arrangement of Calculation Blocks

This study area was horizontally divided into 42 blocks in NE-SW direction and 50 blocks in NW-SE direction (Figure 6) 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 horizontal block arrangement and the position of the magma chamber, the faults and the cap rocks are shown in Figure 7. The location and three-dimensional shape of the magma chamber was determined by reference to the result of the seismic tomography by Yoshikawa et al. (2005), and slightly modified in the modeling process.

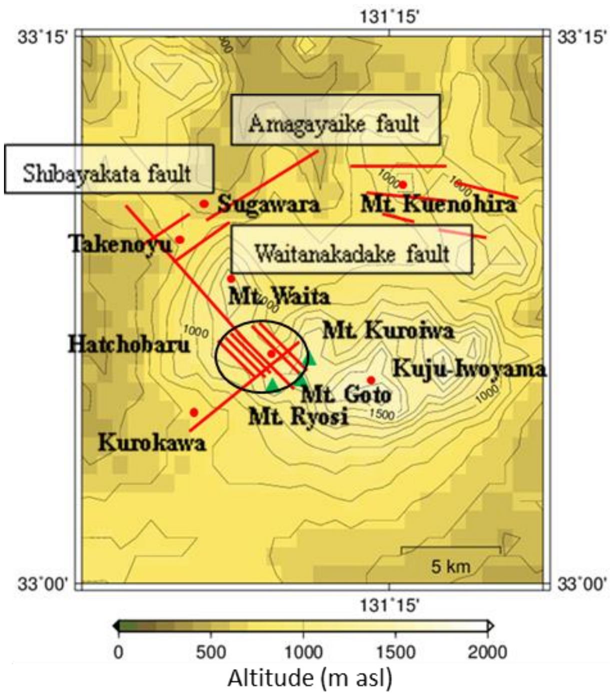

Figure 5: A conceptual model of the Kuju volcanic field (new model).

4.2 Rock Properties

The values of the rock properties are shown in Table 1. These values had been based on a research result by New Energy Development Organization (1984), and modified in the modeling process. The faults at Hatchobaru which was surrounded with a circle in Figure 5 are "fault 2" in Table 1, and it indicates anisotropy. And we referred to the result by Ehara (2007) for the location of a volcanic conduit beneath Kuju-Iwoyama.

Table 1: Rock properties for the most suitable model.

	thermal conductivity (W/m・K)	porosity	horizontal permeability		vertical permeability (m^2)	density (g/cm^3)	specific heat (J/kg・K)
			NE-SW direction (m^2)	NW-SE direction (m^2)			
volcanic rock	1.91	0.12	1.0×10^{-16}	1.0×10^{-16}	2.1×10^{-16}	2.633	919
basement rock	3.28	0.01	1.0×10^{-16}	1.0×10^{-16}	1.0×10^{-16}	2.740	860
cap rock	1.91	0.12	1.0×10^{-18}	1.0×10^{-18}	1.0×10^{-18}	2.633	919
fault	1.91	0.12	40×10^{-15}	40×10^{-15}	1.0×10^{-15}	2.633	919
fault 2	1.91	0.12	1.0×10^{-16}	40×10^{-15}	1.0×10^{-15}	2.633	919
volcanic conduit	1.91	1.91	10×10^{-15}	10×10^{-15}	10×10^{-15}	2.633	919

4.3 Numerical Modeling Process

The calculation conditions for the numerical simulations of the hydrothermal system are shown in Table 2. First, we constructed an initial model that was calculated for 500,000 years with the same boundary conditions as Table 2 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 2). The volcanic conduit was set in this model after 35,000 years have passed since the simulation was started.

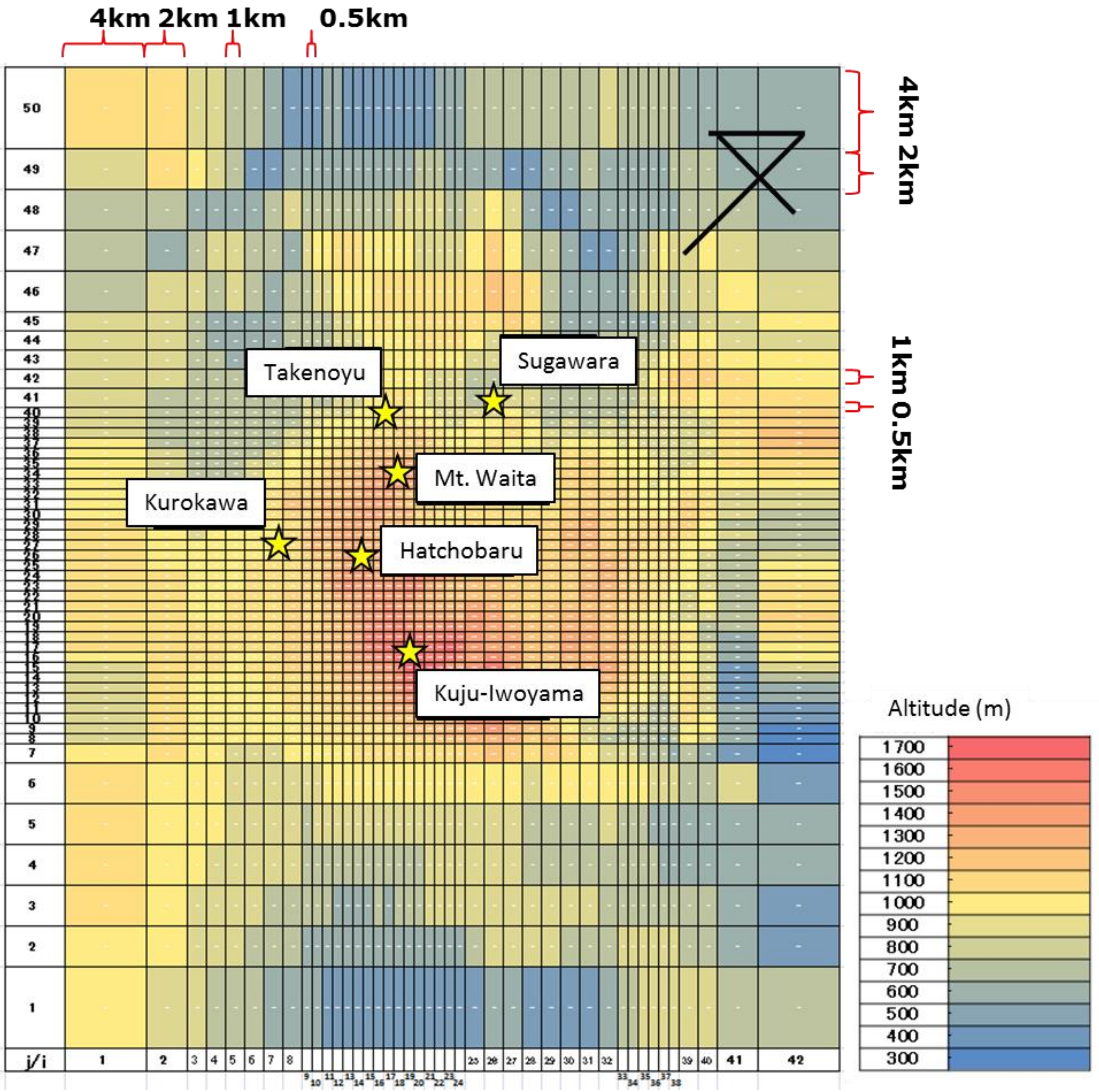

Figure 6: Digitized topographic map of the study area.

Table 2: Calculation conditions for the numerical modeling.

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 field. And the rock properties and the shape of the magma chamber were modified by trial and error to match the calculated and observed temperature profiles. The locations of the wells are indicated in Figure 8.

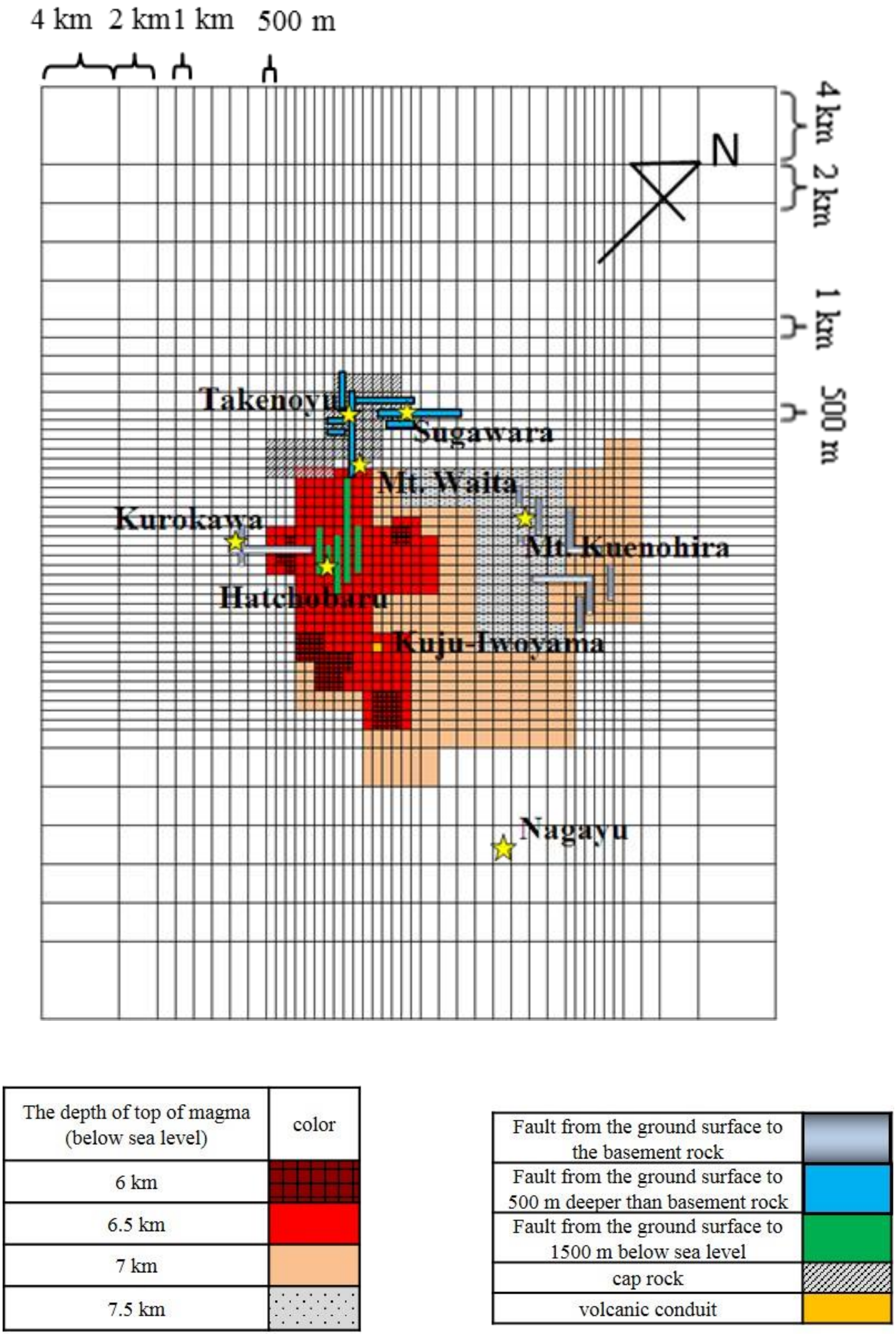

Figure 7: Horizontal block arrangement and locations of a magma chamber, the faults and the cap rocks for the numerical modeling (upper), legends of the depth of the top of the magma chamber (lower left), faults, cap rocks and a volcanic conduit (lower right).

5. RESULTS OF SIMULATION

The calculated temperature profiles of the most suitable model compared with the observed temperature profiles of the wells shown in Figure 8 are indicated in Figures 9 to 12. The temperature profile data of the well were drawn from Japan Atomic Energy Agency (2012). And we also compared the most suitable model with the result of the previous model in the same figures.

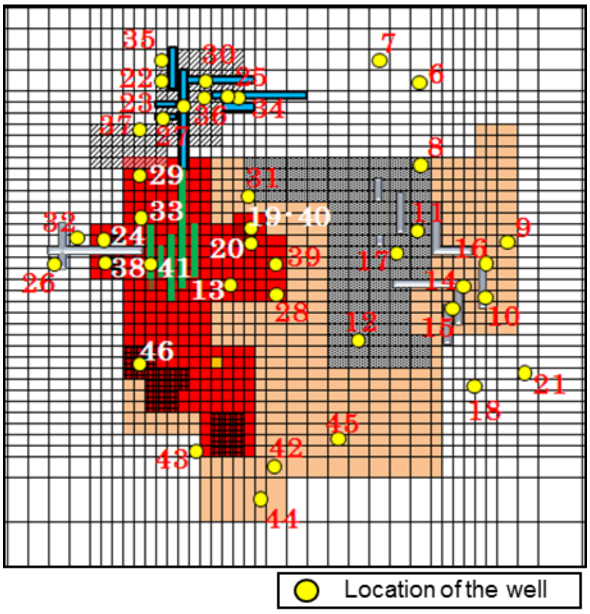

Figure 8: Locations of the wells. The numbers in this figure are the same as those after the well names in Figures 9-12.

5.1 Takenoyu and Sugawara Areas

The temperature profiles of the wells Nos. 23, 34 and 36 are shown in Figure 9. The new model explains the temperature profiles of these areas better than the previous model. Therefore, it would appear that the improved subsurface structures of these areas are appropriate.

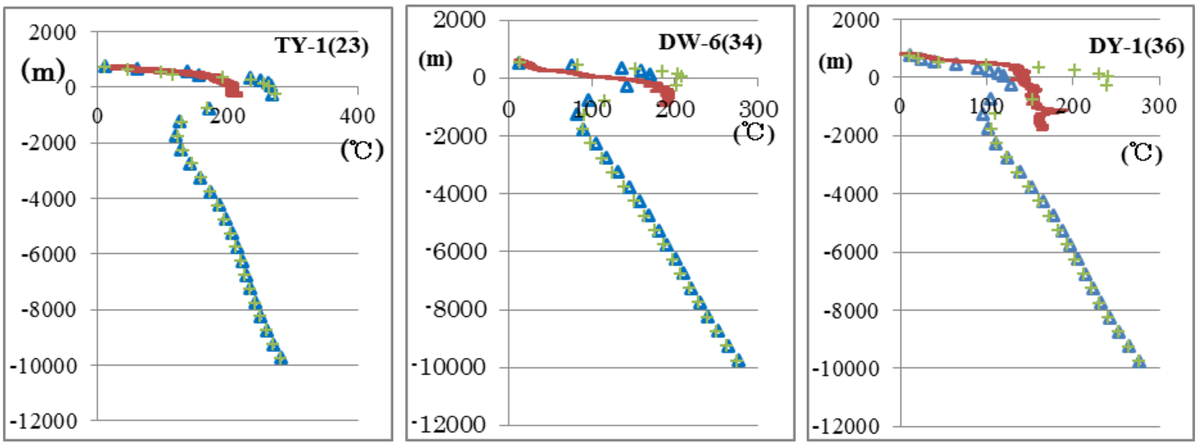

Figure 9: Temperature profiles in the Takenoyu and Sugawara areas (blue triangles: the new model; green crosses: the previous model; red dashes: observed values).

5.2 Mt. Kuenohira Area

Figure 10 indicates the temperature profiles of the wells Nos. 10, 14 and 16 in the Mt. Kuenohira area. The shapes of the calculated temperature profiles express the existence of a hydrothermal system. However, it is difficult to recognize the remarkable improvements from the previous model even though we set some faults around Mt. Kuenohira. Therefore, more consideration about the subsurface structure of this area should be required.

5.3 Hatchobaru and Kurokawa Areas

The temperature profiles of the wells Nos. 26, 38 and 41 in the Hatchobaru and Kurokawa areas are presented in Figure 11. The calculated temperature profile of Well HT5-1 (No. 41), which is near the anisotropic faults in the Hatchobaru area, of the new model is more suitable than that of the previous model. On the other hand, the temperature of Well DB-8 (No. 26) in the Kurokawa area became lower than that of the previous model. It is because the hydraulic anisotropy of the faults in the Hatchobaru area changed the direction of geothermal fluid flow. It means that there is a possibility of another hot water supply for the Kurokawa area.

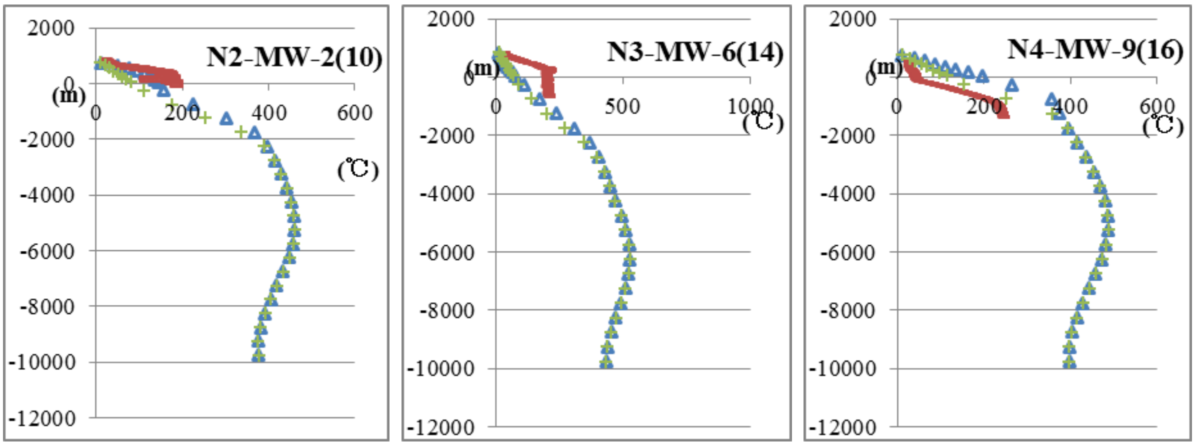

Figure 10: Temperature profiles in the Mt. Kuenohira area (blue triangles: the new model; green crosses: the previous model; red dashes: observed values).

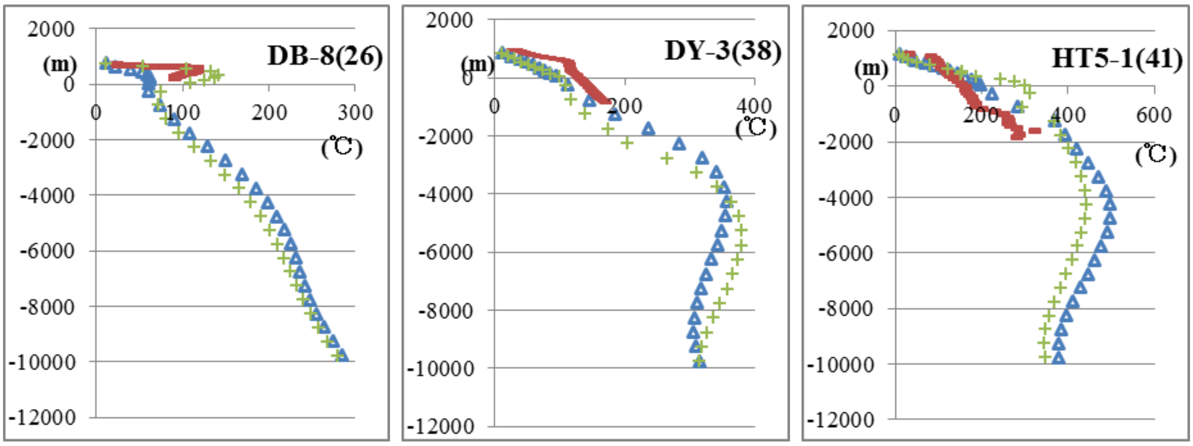

Figure 11: Temperature profiles in the Hatchobaru and Kurokawa areas (blue triangles: the new model; green crosses: the previous model; red dashes: observed values).

5.4 Other Areas

According to Figure 12, which expresses the temperature profiles of the wells Nos. 7, 12, 20, 28, 39 and 42, some results of the new model are better (e.g. Well N2-MW-4 (No. 12)), and some others are worse (e.g. N3-YT-2 (No. 20)) than the previous model, but most results don't change. We need to consider the subsurface structure more to explain the hydrothermal systems of these areas.

6. CONCLUSION

As a result of our study, the most suitable numerical model replicates the hydrothermal systems of the geothermal power station areas roughly although the numerical model is not so complicated, and the new model is more appropriate in the Takenoyu and Sugawara areas and the Hatchobaru area than the previous model. In the meanwhile, there are still some points to improve. We need to consider the subsurface structure of this volcanic field more to explain the hydrothermal systems of the wider area.

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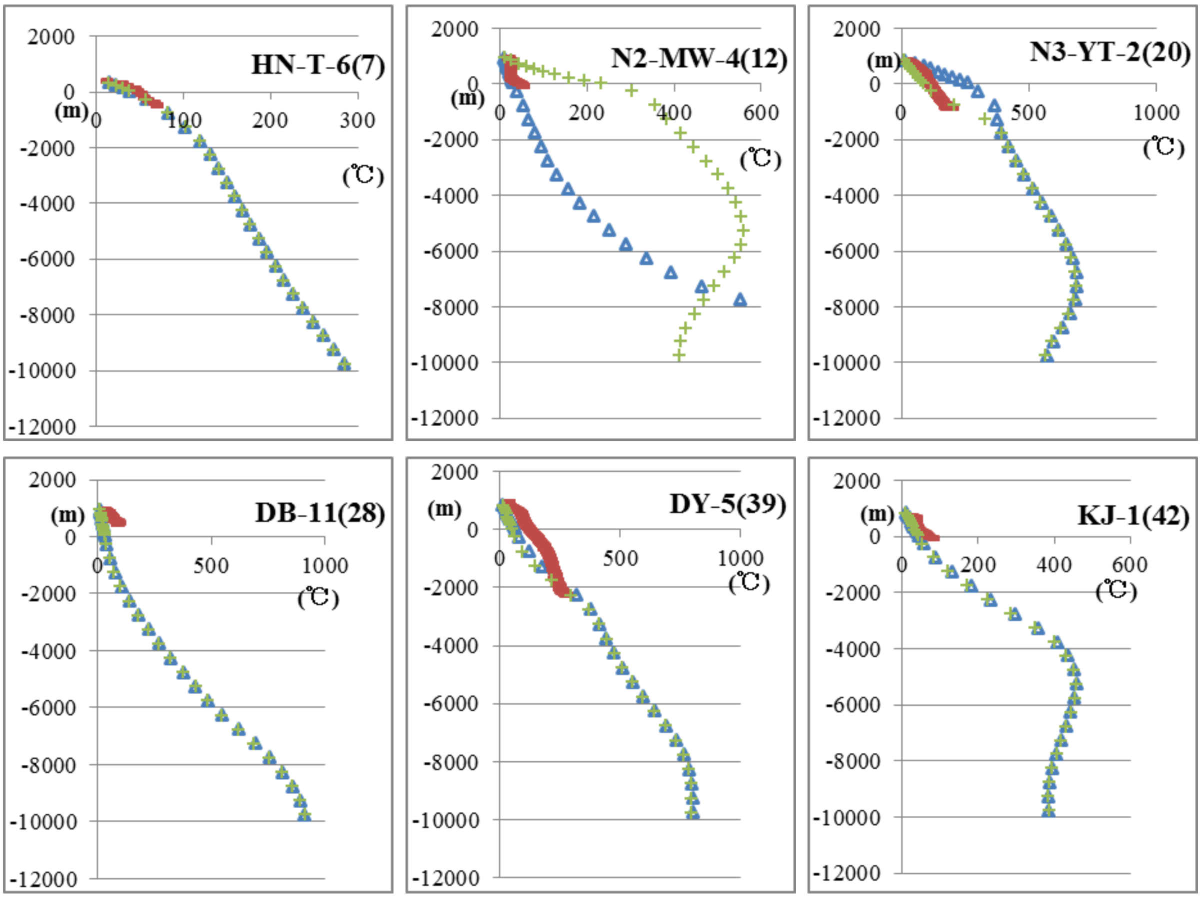

Figure 12: Temperature profiles in other areas (blue triangles: the new model; green crosses: the previous model; red dashes: observed values).

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