Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Current Geothermal Development in Kumamoto Prefecture, Central Kyushu Island, Japan

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Keywords: Geothermal field, Kumamoto, Numerical simulation, Case study, Hot spring, Aerial gravity survey

ABSTRACT

Kumamoto is in the centre of Kyushu Island in Japan with much of geothermal resources. The geothermal energy development is strongly desired for the completion of the energy policy. The Oguni geothermal field is located in the north of Kumamoto Prefecture. The Hacchobaru and the Otake Geothermal Power Plants are placed near this field. A 2 MW geothermal power plant commenced in operation at the Oguni field but more than 20 MW electricity generation is expected by the previous potential estimations. The estimation was based on the numerical simulation with a conceptual model where geothermal fluid flows north-westward along a fracture fault but turns north on the way. From the topographical point of view the fault is clearly found near the mountain area, where ascending geothermal fluid is expected, but it becomes unclear far from the mountain.

An aerial gravity deviation survey was recently conducted in this area and shows the gravity continuity, suggesting a path of hydrothermal activity. Based on the analysis geothermal fluid flows up under the mountain and flows directly to the other geothermal field where a 5MW binary power plant is in operation. We have reviewed published models in the previous studies and carried out the numerical simulation based on the new model.

1. INTRODUCTION

After the terrible disaster at the Fukushima Nuclear Power Plant happened in March, 2011, demand for stable and renewable energy supply has been increasing not only less supply electricity by nuclear power plants but also against the global warming. Agency for Natural Resources and Energy, one of the METI's (Ministry of Economy, Trade and Industry) departments approved and announced "The Long-term Energy Supply and Demand Outlook" on 16 July 2015 pursuant to the policies of the Strategic Energy Plan, which includes the electricity generation mix (as call as "Energy Mix") to the year of 2030. Figure 1 shows the energy mix in the past and in 2030 (METI, 2015). Electricity generation by renewable energies is set at 22% to 24% of total electricity supply in 2030, though coal, LNG, and nuclear are set at 26%, 27% and 20% to 22%, respectively. If the plan is realised, CO_2 emissions would be 21.9% lower than in 2013, and the primary energy self-sufficiency rate would increase from 6.3% in 2012 to 24.3% in 2030. On the basis of this political decision geothermal energy is expected to generate at 1.0 to 1.1% of total generation. The amount of the electricity generation by geothermal is estimated to be 1,500MW, which is roughly about three times at present (500MW as of March 2018) (Thermal and Nuclear Power Engineering Society, 2019).

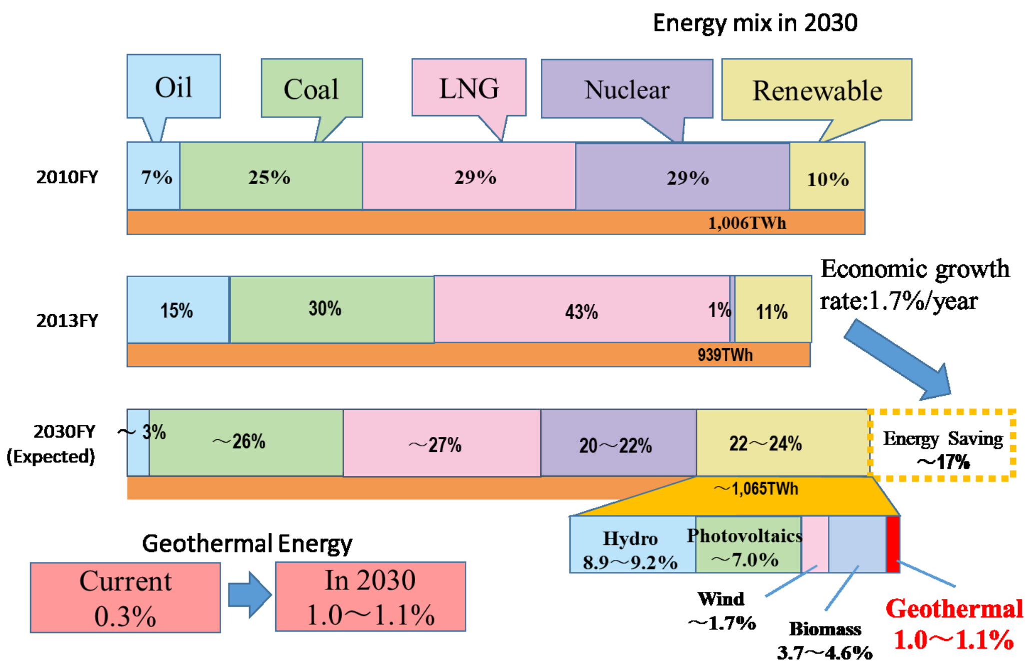

Figure 1: Electricity generation for each resource in 2030 (Energy Mix). Geothermal energy is expected about 1.0% of total electricity generation, which is almost three times. (after http://kankeiren.or.jp/keizaijin/15_8%20now.pdf)

Geothermal energy is recognised as one of environmentally harmonized energy resources and this recognition is widely known and accepted. There are, however, various obstacles against the development. Three major obstacles are recognised in Japan. The first obstacle is a long time necessary to the development from the first survey to the construction of the power plant and the second is national parks where development is restricted very much although a lot of resources exist in the park. The last one is the opposite opinions of local residents. There are many cases where local residents cannot understand the meaning of the development and warry about the depletion of the hot water supply in their hot springs. This last obstacle is often caused by "hot spring culture" which is quite unique in Japan.

The opposite opinion that the geothermal development affects the serious damage to hot springs often happens outside of the developing area and it sometimes causes the suspension of the development. It is undeniable that lack of risk communication has caused the background of discontinuation of development. It is also impossible for the current science to understand the impact to the underground environment exactly during the development. Therefore, the several kinds of monitoring observations, such as temperature, water level, geochemical components, are necessary to be carried out at hot springs around the developing area where the influence is concerned. However, it is also hard to interpret the monitoring results because there are variations caused by the various reasons. Simulation with a numerical model helps for the interpretation because it is easy to display the flow change of the geothermal fluid according to the output of the numerical calculation. The numerical simulation is, of course, useful to estimate the geothermal potential and/or the effects of injection and production of geothermal fluid. In this paper we will discuss on the simulation study at the geothermal fluid in Kumamoto.

2. GEOTHERMAL FIELDS IN JAPAN

2.1 Geothermal field in Kyushu

The geothermal field in Japan is mainly found in Hokkaido, Tohoku, and Kyushu regions and the geothermal systems are formed by the different geological and tectonic situation among these regions (Figure2). The major geothermal fields in Hokkaido are located in the middle of the island caused by the collision, and those in Tohoku are caused by a typical trench-subduction system. On the other hand, in the Kyushu area, the geothermal fields in the southern part of the island are also associated with volcanoes caused by a trench-subduction system, but those in the northern part are formed by the expansion tectonic area, which is the unique geological condition in Japan.

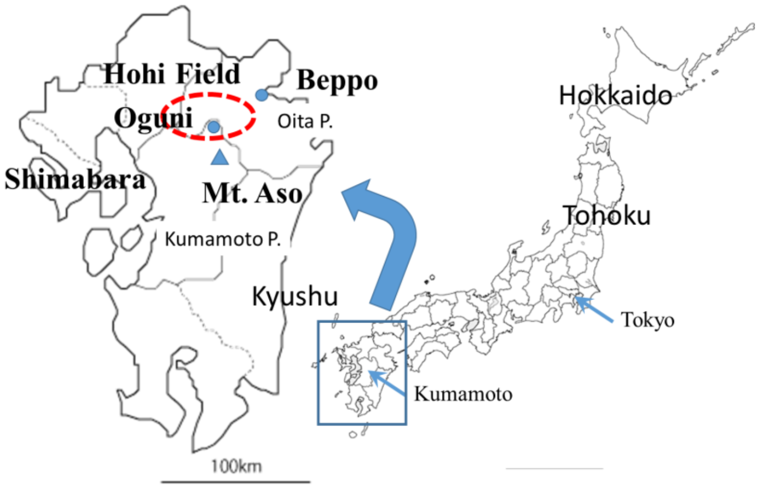

Figure 2: The locations of Kyushu and Kumamoto Prefecture. The Ogini geothermal field is located in the north of Kumamoto Prefecture with in the Hohi geothermal area.

In Kumamoto two major geothermal areas are located. One is the Hohi geothermal area and the other is the Minami-Aso geothermal area. The former is located in this expansion tectonic area and is expanded in Kumamoto and Oita Prefectures. The latter geothermal area spreads to the south side of Mt. Aso. However, the development at this area has been delayed and suspended because of the earthquake. The Kumamoto Earthquakes started to happen on 14th April 2016 and two major shocks were recorded with the maximum magnitude (JMA Scale) of 6.5 and 7.3. These earthquakes were caused by the movement of the tectonic faults about 30 km southwest of Mt. Aso but several damages in and around the Minami-Aso geothermal area were caused. The restoration of infrastructure such as roads and bridges was firstly prioritised after the disaster. At one geothermal field in the Minami-Aso area a production well was drilled but most of the plans for the geothermal energy development were delayed and postponed.

2.2 Hohi geothermal area

Hohi geothermal field is known as a volcano-tectonic depression region formed under a tensile stress field after the Neogene time. Geological conditions are well represented in Figure 3, which shows a Bouguer anomaly map around the Hohi geothermal area (AIST, 2013). The Beppu-Shimabara graben is characterized by low gravity anomalies, which extends from the Beppu Bay to the Shimabara Peninsula. There are uplifting and subsiding zones in this graben. The Kuju uplifting zone has a trapezoidal shape from a topographical view point, and the northeast margin of this uplifting zone forms steep slope. The Shishimuta subsiding zone is also located in the graben and contacts to the Kuju uplift zone (Fujita and Abe, 1988).

Fractures with faults in northwest-southeast direction associated with geothermal resources are expected in the steep slope. Other fractures in northeast-southwest direction intersect orthogonally to the previous fractures in this area. Geothermal resources with high permeability have been developed. Lineament has also developed in northwest-southeast and northeast-southwest directions. The

Shishimuta subsiding zone is originated of a caldera that was active from about 1 Ma to 900 ka, and this caldera spurted a large amount of pyroclastic flow (Gyagyo pyroclastic flow and Imaichi pyroclastic flow) by two large eruptions. Geothermal systems are expected in the steep slopes around subsiding zone, and the Hohi geothermal area placed around Shishimuta subsiding zone is regarded as a typical geothermal field in Japan (eg. Kamata, 1989).

2.3 Oguni geothermal field

The Oguni geothermal field is near the Okake and the Hacchobaru Geothermal Power Plants, where EPDC (Electric Power Development Co. Ltd, currently J-Power) started to develop in 1983 and planned to construct a geothermal power plant with an install capacity of 20MW. However, EPDC resigned the development in 2003 because of disagreement of few local people. No promotion of the development had been carried out since the retreat of EPDC. In 2016 a company invested by locals commenced in operation with a conventional geothermal power plant, the Oguni Power Plant, with a 2 MW steam generator.

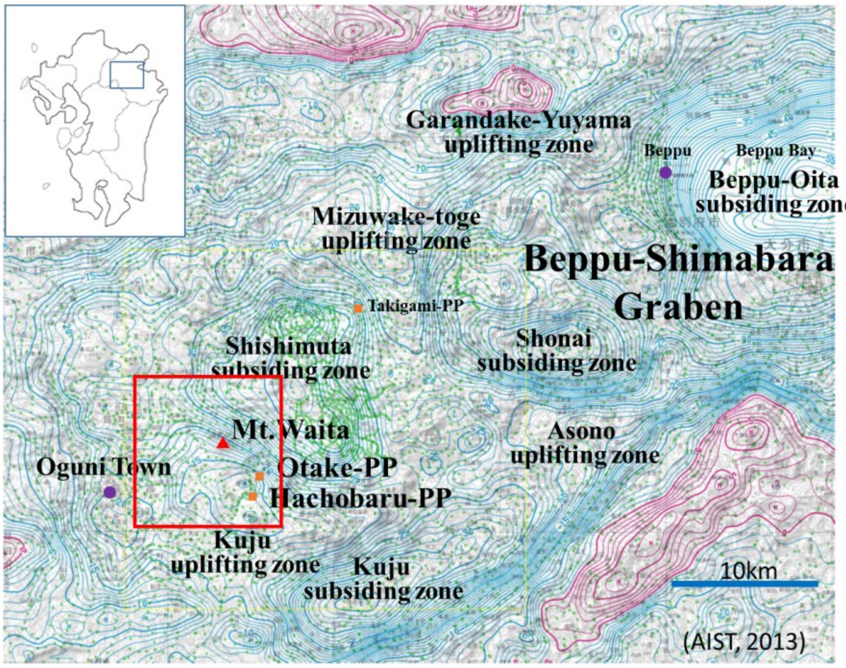

Figure 3: Subsiding and uplifting areas on the Bouguer anomaly map. A red solid square shows the boundaries of the area for this study, which are also shown in Figure 4, in the Hohi geothermal area.

The hydrological and hydrothermal characteristics of this field structure were compiled and summarised by Yamada et al. (2000). Geothermal fluid is generated terrestrial water (rain flow) heated by the heat source located under Mt. Waita. Two heated fluid flows are mainly recognised from the heat source and create geothermal reservoirs, which are extensively fractured, horizontally layered, and are subdivided into northern and southern reservoirs. Both reservoirs contain dilute NaCl liquid brines at temperatures from 200 to 240°C and small steam zones are present at the top of the reservoir. At the northern reservoir steam fluid flows out on the surface and creates hot springs. The northern reservoir covers a large area and has relatively high permeability (kh = 100-250 Darcy m).

The geothermal fluid comes up from the bottom of Mt. Waita and flows in the northwest direction along the Takenoyu Fault represented by conventional hydrothermal models (eg, Fujimitsu and Yuhara, 1989). The flow changes its direction to the north at the impermeable zone estimated by the well logging data and reaches to the Sugawara Binary Power Plant with a 5 MW generator. The Takenoyu Fault is characterised by the valley topography on the surface and is believed to be constructed with a highly permeable fracture system at the subsurface (Nakanishi et al., 2000).

2.4 Geophysical survey by a helicopter

The geothermal fields in Japan are mostly associated with the Quaternary volcanoes and distributed in mountainous areas or within national parks, where it is difficult to access and to investigate. The survey is especially restricted for the development in the national parks. Some of the national parks are located near volcanoes and geothermal resources are associated with the volcanoes. About 80% of the geothermal resources are located in the natural parks. The heli-borne survey is an effective method to acquire data over a broad area without modification of the land surface (JOGMEC, 2015).

Gravity gradient and resistivity surveys are conducted and measured by a helicopter. The survey using a helicopter (heli-borne survey) has an advantage of its lower flight altitude and slower speed than that using an aircraft, implying that the stronger signals and denser survey points are obtained. The investigation area of 300 to 500 km^2 is basically selected, where the geothermal resources are expected. Spatial filters are applied to the heli-borne gravity gradient data and some filters reveal the geological structure concordant with the faults and fractures. Shape Index (SI) representing the shape of the equal gravity potential plane has been proposed (eg. Koenderink and can Doom, 1992; Cevallos et al., 2013). SI is attended to focus on the curvature of the potential surface such as gravity with values from -1 to 1 and shows 1 (Cap) when the gravity potential plane is bulging upward, 0(Saddle or Flat) when it is saddle or flat, and -1 (Cup) in the shape of a bowl dropping downward (Figure 4). It can be calculated by the following formula,

$$\mathrm{SI} = \frac{2}{\pi} arctan \left[\frac{\frac{\partial G_z}{\partial z}}{\sqrt{\left(\frac{\partial G_x}{\partial x} - \frac{\partial G_y}{\partial y}\right)^2 + 4\left(\frac{\partial G_x}{\partial y}\right)}} \right] \quad (1)$$

where G_x, G_y, and G_z are special derivative of gravity potential G in x, y, and z directions, respectively.

SI is possible to process the shape of the gravity basement numerically. Tosha et al. (2018) analysed the data taken by gravity gradient survey and revealed the gravity structure in the Oguni geothermal field, implying that the structure is clear extending linearly from Mt. Waita to the Sugawara Binary Power Plant, and it might be possible to estimate the underground fracture system that is oblique to the Takenoyu Fault on the surface and is a possible fluid path in the northern geothermal reservoir in the Oguni field.

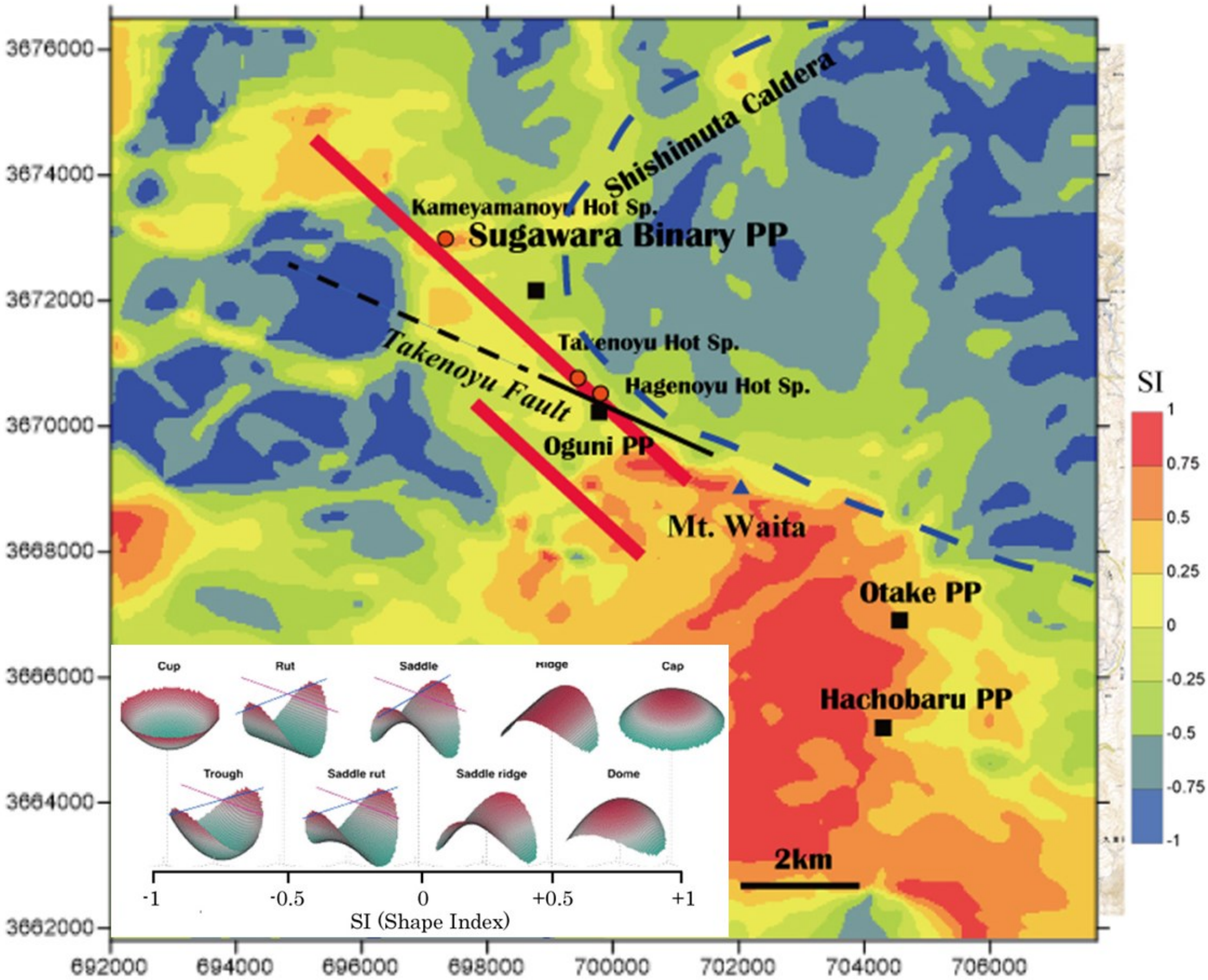

Figure 4: Shape Index (SI) analysis using the gravity gradient data taken by a helicopter. The interpretation of the shape of gravity basement is also shown. Fracture system should expect to be developed along the steep slope of the gravity, which is shown as the pair of the cap and cup structures. Two fracture systems are extracted shown in red thick lines after Tosha et al. (2018).

3. MODELS IN THE OGUNI GEOTHERMAL FIELD

3.1 Geological settings

As mentioned at the previous chapter, Oguni geothermal field is located in the Hohi geothermal area along the Shishimuta subsiding zone. There are several geological layers but most of the layers are composed of the volcanic rocks and ashes (Fujita and Abe, 1988). Oguni geothermal field is divided into two reservoirs, the northern and the southern reservoirs. The Takenoyu Fault is trending in the northwest - southeast direction and is recognised as the major part of the northern geothermal reservoir. A few ground surveys were performed at the southern geothermal field and no development has been performed. Lower permeability is expected at the southern reservoir. Several geological layers composed of thermal alternated rocks are found at many wells and they work as cap rocks to prevent the diffusion of the geothermal fluid into the surface. The depths of these alternated rock layers are about 200 m and 300 m below the surface. In this study simulation study is focused on the northern geothermal reservoir because less wells have been drilled and few geophysical surveys have been carried out in the southern geothermal field.

3.2 Conceptual model

In the hydraulic model of the northern reservoir, hot water heated by heat source under the Mt. Waita rises along the Takenoyu fault and moves north-westward. The geothermal hot water changes to the north at the estimated impermeable zone. The Takenoyu fault is clearly found near the mountain from the topological point of view but it becomes unclear far from the mountain. In the previous studies hot geothermal fluid is generated under the Mt. Waita and moves to west along the Takenoyu fault. The flow turns it direction to the north and reaches to Sugawara. The cap rocks are set at about 200 m below surface.

Recent survey of the measurement of aerial gravity deviation survey resulted in continuity from the Mt, Waita to Sugawara, which suggests a path of hydrothermal activity. This flow path need not change flow direction on the way. If this fracture system is responsible for the geothermal activity in Oguni field, it can explain that the geothermal fluid generated under the Mt. Waita reaches Sugawara directly and also reaches the Kameyamano-yu hot spring ahead. Moreover, another fracture system through which geothermal fluid passes in south of the Takenoyu fault is also expected in the analysis of the gravity deviation survey. The geothermal flow should supply hot water in the southern Oguni geothermal field. In this study simulation should be carried out based on this model.

By contrast, the reservoir at the southern geothermal field covers a relatively small area and has limited transmissivity. The undisturbed stable reservoir pressure in the southern reservoir exceeds that in the northern reservoir by about 1 MPa, indicating little connectivity between two reservoirs. The permeability structure of the field has been discussed in detail by Garg and Nakanishi (2000). Geothermal fluid flows up under Mt. Waita in the southern geothermal field but different ascending point rather than that in the northern field. It should be better to construct simulation model for the study in the southern field. The simulation of the southern field will be carried out in feature.

3.3 Simulation code

TOUGH2 is a numerical simulation program for fluids and heat flows, which was firstly released in 1991 and revised in 1999 (Pruess, 1991; Pruess et al., 1999), and have been used for more than 20 years in the geothermal studies. This program covers various geophysical subjects not only geothermal reservoir engineering but also nuclear waste isolation, Carbon Capture and storage (CCS) and environmental subjects in various media and aquifers. Therefore, the TOUGH2 code has "EOS (Equation of State)" modules that handle different fluid characteristics, and uses a module compiled by changing "EOS" according to the type of liquid and/or to the target of the analysis. EOSs are listed in Table 1. EOS1 and EOS3 are frequently used in the simulation of the geothermal fluid and we used both EOSs for our study. The module of ECO2N was also developed for the analysis of the CO_2 fluid in the CCS (Carbon Capture and Storage) study (Pruess, 2005).

Table 1. EOSs of TOUGH2 simulator

EOS1	water, water with tracer
EOS2	water, CO2
EOS3	water, air
EOS4	water, air, with vapour pressure lowering capability
EOS5	water. hydrogen
EOS7	water, brine, air
EOS7R	water, brine, radionuclide1, radionuclide2, air
EOS8	water, air, oil
EOS9	wsaturated-unsaturated flow
EWASG	water, NaCl, non-condensible gas

3.4 Simulation model

In the numerical simulation, the model was defined by a grid in the directions of three orthogonal axes (XYZ). The direction from the Mt. Waita, where the geothermal fluid generates, to the Sugawara Binary Power Plant is taken as the X direction and the direction orthogonal to the X direction is taken as the Y direction. The Z direction is vertical.

The size and number of blocks are 5,800 m and 26 blocks in the northwest (X) direction, 4, 700 m and 23 blocks in the northeast (Y) direction, and 3, 400 m and 19 blocks in the vertical (Z) direction, respectively. The total number of blocks was 11,362. The model is shown in Figures 5 and 6. In this simulation, the hydrothermal fluid is assumed to blow up subsurface region under Mt. Waita and along the fracture system. The basement layer with low permeability is set at an altitude of -1200 m or less according to the gravity basement analysis (AIST, 2013) and the upward flow is generated at a high permeable block in the basement layer. Hot water flows into the model from the bottom of the model and moves in the northwest (X) direction to form a hydrothermal reservoir system.

Also, it was assumed that water of 15 °C. was accumulated in each block as an initial state. Moreover, closed boundary conditions are made at the bottom and at the three side surfaces except the outflow side of a hot water. The number and position with open boundary for the outflow of hot water were calculated in several cases and the most suitable conditions was obtained. Topographic elevations are also considered, where the upper surface of each block is in contact with the atmosphere with a constant temperature and pressure. A block with infinite volume is connected to the open boundary block to satisfy the open condition. Therefore, geothermal fluid flows out through the open boundary blocks.

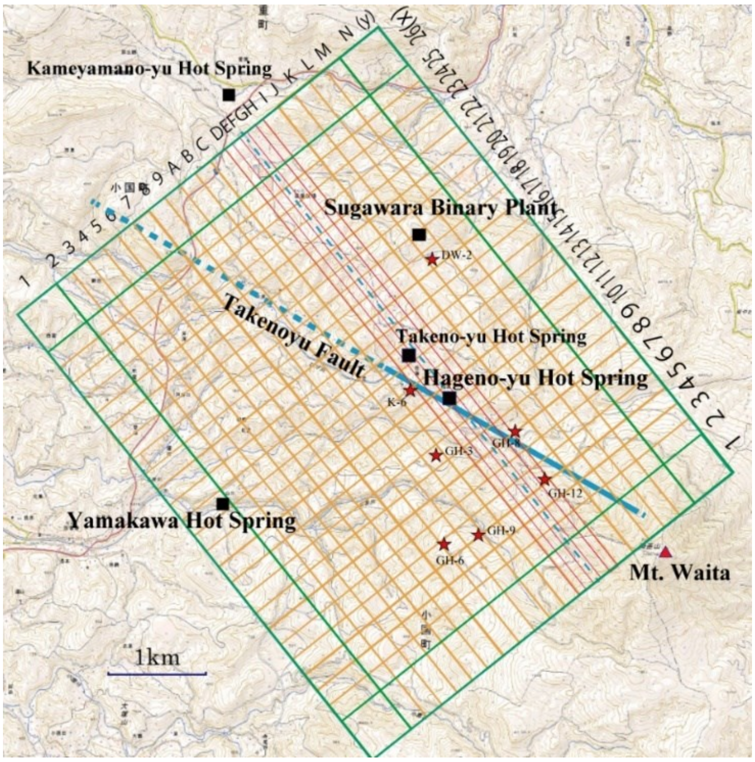

Figure 5: The grids for the calculation of fluid flow by TOUGH2 simulator. The geothermal fluid flows up at Mt. Waita and to the Sugawara Power Plant and Kameyamano-yu Hot Spring along the x direction. The fluid flow path is assumed to be oblique to the conventional path flow along the Takenoyu fault. The wells, which we used to adjust simulation parameters, are also shown as star symbols. Air blocks are set according to topography and the depth of the basement was estimated based on the analysis using the gravity data.

Initial state simulation was performed by changing the parameters described below. 1 million years after the start of inflow of hot fluid was assumed as the calculation period. Also, in many simulation studies, the permeability in the horizontal (X and Y) directions is 1/3 to 1/2 of that in the vertical (Z) direction, so in this study the permeability in the X and Y directions is set to be 1/2 of that of the Z direction.

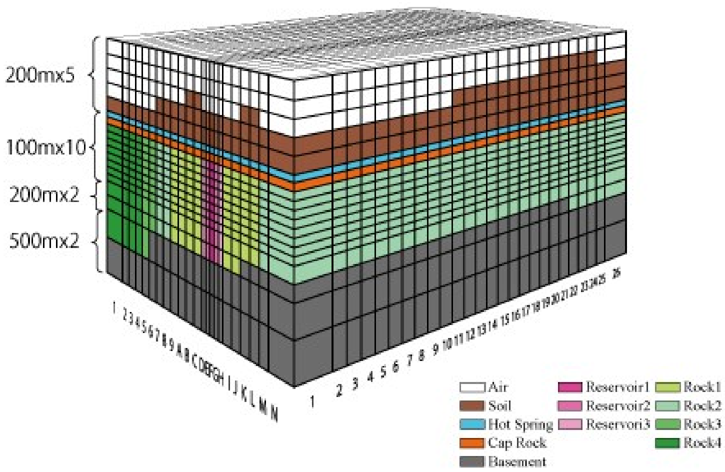

Figure 6: The blocks for the calculation. Air blocks are set according to topography and the depth of the basement was estimated based on the analysis using the gravity data.

4. RESULTS AND DISCUSSION

Since the inflow rate is unknown, calculations were made on the assumption of various cases, and the optimal inflow rate was determined by history matching with the well logging data.

4.1 Boundary blocks

The hot fluid flows into the model from the heat source under Mt. Waita, and ascends and diffuses into the highly permeable reservoir. The fluid flows out at the open boundary blocks on the opposite side. The numbers and position of the open boundary blocks were examined.

The position of the open boundary block was assumed to be located at the depth below the cap rock and around the opposite position to the hot fluid inflow point (Y = E). In the case of 4 open boundary blocks, temperature of the model becomes generally high because the heat remained in the model (Figure 7). On the other hand, a model with 40 open boundary blocks leads low temperature. Based on these analysis results, the number of the open boundary was set to 12 blocks

4.2 Temperature of the inflowing water

The enthalpy of the inflowing hot water was selected by trial and error. The initial temperature is fixed at 15 °C. Temperature logging results in the investigation wells show the hot water temperature is close to the range of 200 °C to 250 °C. We have tried to carry out the simulation for the inflowing temperature between 200 °C and 250 °C. The conduction heat sources were also experimentally put at the lower surface of the model, but the heat source alone was not able to heat the reservoir of this analysis. Therefore, the effect of heat conductive heat source is finally excluded.

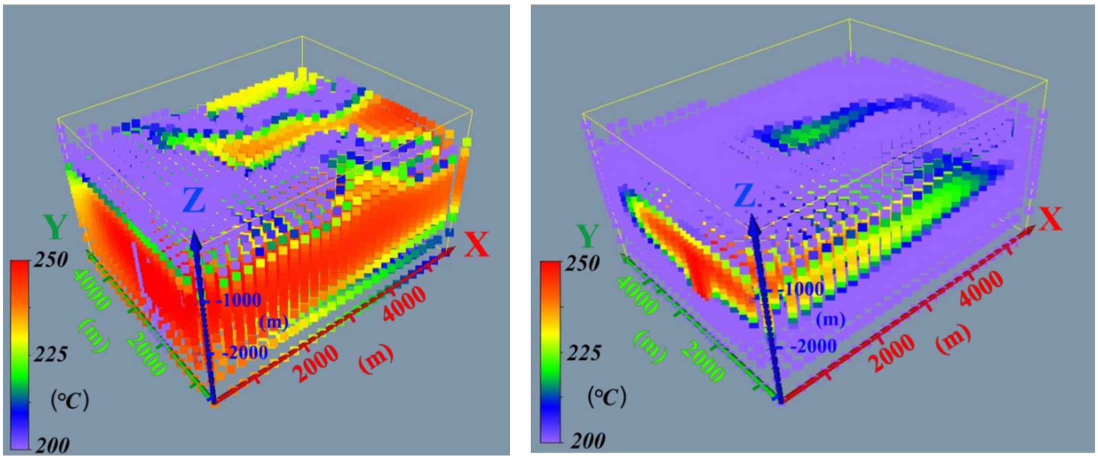

Figure 7: Temperature distribution in the model with 4 (left figure) and 40 (right figure) blocks as open boundaries. As the number of open boundaries is increased, heat escapes out of the model and the temperature in the model remains low.

4.3 Physical properties

Each block was roughly classified into reservoirs, caprocks, soil, basement, and volcanic rock layers based on geological maps and well bore logging data though several rock types were assumed at the simulation model (see Figure 6). The standard values of the physical property are initially given for permeability, porosity, density and heat conductivity of each formation. Temperature of geothermal fluid and amount of inflow are also examined and tuned based on the result of simulation.

Since heat is mainly transferred by convection in the layer below the caprock and the permeability is considered to be most relevant, we adjusted the permeability preferentially. Moreover, since the convection is hard to occur in the layer above and including the cap rock, the porosity was also adjusted (Table 2). Finally, the input rate and enthalpy of the hot water were set to 10 kg / s and 9.61 J/Kg, respectively, which corresponds to hot water temperature of 200 ° C.

Table 2. Typical physical parameters for rock blocks obtained in the simulation

Rock Type	Density (kg/m3)	Porosity (%)	Permeability (m2)	Thermal Conductivity (W/m°C)	Specific heat (J/Kg)
Soil(above caprock)	2000	10	0.5x10-16	0.8	2050
Rock(volcanic layer)	2200	5	1.0x10-16	1	1050
Caprock	1800	0.1	1.0x10-20	0.01	2050
Reservoir	1800	20	100x10-16	0.7	1050
Basement	2600	5	1.0x10-16	2	1050
Air	0.25	10	10x10-16	1.4	840000

4.4 Temperature profiles

Calculations are performed by adjusting the rock parameters (permeability, density and thermal conductivity) of the reservoir, and comparisons of the calculation results with the temperature distribution obtained from the survey well GH-6, GH-9, and DW-2 are shown in Figure 8.

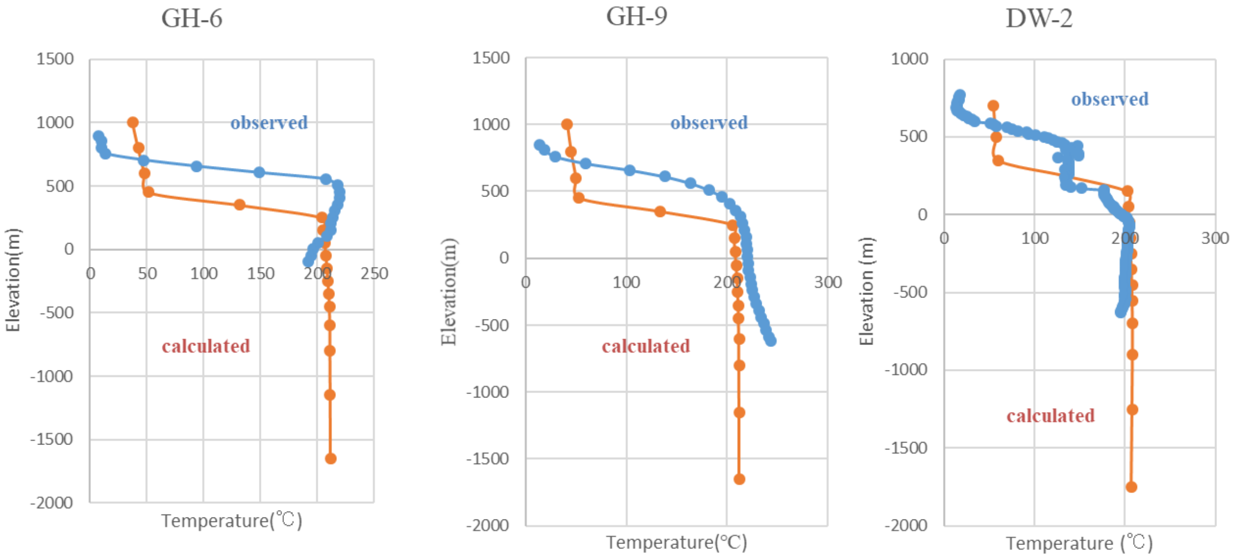

Figure 8: Comparisons of observation data and calculation results. The calculation explains the actual measurements in each well. However, as the cap lock was set to the same depth at the whole area, it is suggested that the actual depth is different from the depth in the model.

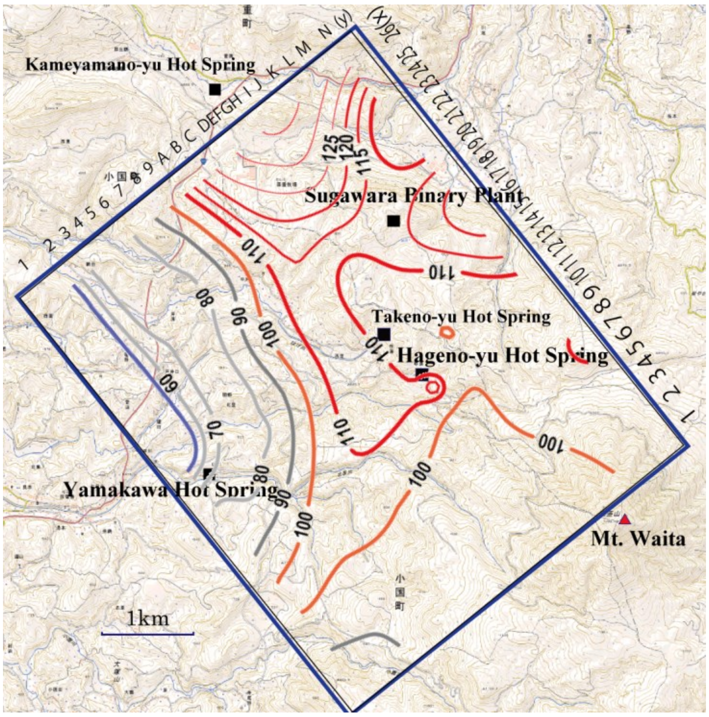

Figure 9: Fluid flow simulation for the shallow hot spring water layer. Hot spring fluid is generated at Hageno-yu spring and flows laterally at the shallow fracture zone above cap rocks.

4.5 Fluid flows at a shallow layer

In the hydrothermal flow simulation model, blocks indicating a hot spring aquifer are set on the cap rock blocks. In order to examine the flow of the hot spring water in the model, which was finally obtained after adjusting the parameters, heat is supplied to a hot spring block by increasing the permeability of the cap rock block just below Hageno-yu, a hot spring along to the Takenoyu fault in Oguni geothermal area and closer to the expected up flows of geothermal fluid in the Mt. Waita. In order to discharge hot water from the hot spring, several blocks with open boundary are placed in the northwest of the blocks corresponding to the hot spring layer, where the hot spring water outflows.

4.6 Further study

The simulation model based on new survey results was constructed and the initial state simulation was carried out using this new model. The main theme of this study was to build a model that can roughly explain the reservoir in Oguni geothermal field, so there is a small gap between the simulation results and the actual data in detailed parts.

In the future, it will be necessary to make revisions such as making the blocks smaller in areas that need more detail studies. Also, the grid spacing was calculated on the basis of 100 m for the vertical direction, but a finer 20 m grid spacing will be required for the simulation of the steam layer or the hot spring. A comprehensive model must be constructed in order to achieve this simulation. It is also necessary to review the model technique to study both northern and southern reservoir in the Oguni geothermal field.

6. CONCLUDING REMARKS

In order to simulate hydrothermal flow at Oguni Geothermal Field in Kumamoto, a model was constructed based on the fracture system suggested by the survey result of the airborne physical exploration. As the grid spacing and rock properties are rough determined, the best matching solution was not obtained, but using this model, the flows in the deep geothermal reservoir as well as at the shallow hot spring aquifer are able to be calculated. In the future, it is necessary to construct a model combined together with both the southern and the northern fields in Oguni and to carry out simulations for resource assessment of the entire Oguni geothermal field.

ACKNOWLEDGEMENTS

We would like to express our appreciation to Koichi Yokoi of Mittetsu Mining Consultant, Tatsuya Sato of GERD, and Hiroyuki Tokita of West JEC for the help of parameter setting of TOUGH2 simulator. We also thank to Prof. Kozo Obara of Kumamoto University for the kind support of our study.

REFERENCES

AIST (National Institute of Advanced Industrial Science and Technology) : Gravity database of Japan, DVD edition, (2013).

Cevallos, C., Kovac, P. and Lowe, S.J.: Application of curvatures to airborne gravity gradient data in oil exploration, *Geophysics*, **78(4)**, (2013), G81–G88.

Fujimitsu, Y. and Yuhara, K.: Numerical model of Takenoyu-Sugawara geothermal area and an interpretation of a low resistivity zone with KYU88-1, the simulator for thermal water flow, *Journal of the Geothermal Research Society of Japan*, **11**, (1989), 285-306 (in Japanese with English abstract).

Fujita, T. and Abe, M.: Survey of Oguni geothermal field, Kyushu district, Japan, *Chinetu(Geothermal)*, **25**, (1988), 287-314 (in Japanese with English abstract).

Garg, S.K. and Nakanishi, S: Pressure interference tests in a fractured geothermal reservoir: Oguni geothermal field, Northern Kyushu, Japan, in Dymanics of Fluids in Fractured Rock, *Geophysical Monograph*, **122**, (2000), 363-375.

JOGMEC: Report to examine methods for using airborne survey data of gravity measurement, (2015), p.246 (in Japanese).

Kamata, H.: Shishimuta caldera, the buried source of the Yabakei pyroclastic flow in the Hohi volcanic zone, Japan, *Bulletin of Volcanology*, **51**, (1989), 41-50.

Koenderink, J. J., and van Doornm A. J. ︓Surface shape and curvature scales, *Image and Vison Coputing*, **10**, (1992), 557-564.

METI: The Long-term Energy Supply and Demand Outlook, (2015), https://www.meti.go.jp/english/press/2015/0716_01.html

Nakanishi, S., Pritchett, J.W., and Tosha, T.: Changes in ground surface geophysical signals induced by geothermal exploitation - Computational study on a numerical reservoir model for the Oguni Geothermal Field, *Geothermal Resources Council Transactions*, **25**, (2001), 26-29.

Pruess, K.: TOUGH2: A general-purpose numerical simulator for multiphase fluid and heat flow, *Report LBNL*-**29400**, Lawrence Berkeley National Laboratory, Berkeley, CA (1991).

Pruess, K.: ECO2N: A TOUGH2 fluid property module for mixtures of water, NaCl, and CO_2, *Report LBNL*-**57952**, Lawrence Berkeley National Laboratory, Berkeley, CA (2005).

Pruess, K., Oldenburg, C. and Moridis, G.: TOUGH2 User's Guide, Version 2.1, *Report LBNL*-**43134**, Lawrence Berkeley National Laboratory, Berkeley, CA (1999).

Thermal and Nuclear Power Engineering Society: Present status and trend of geothermal generation in 2018, Tokyo, (2019), p.137.

Tosha, T., Kida, Y., Obara, Y., Yamazaki, T., and Watanabe, H. et al.: Geothermal Development in Oguni, Central Kyushu, *Proceedings*, 43th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2018).

Yamada. M., Iguchi, K., Nakanishi, S. and Todaka, N.: Reservoir characteristics and development plan of the Oguni geothermal field, Japan, *Geothermics*, **29**, (2000), 151-169.