DEEP GEOTHERMAL STRUCTURE AND THE HYDROTHERMAL SYSTEM IN THE OTAKE-HATCHOBARU GEOTHERMAL FIELD, JAPAN

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SUMMARY – For the study-project of NEDO to evaluate the deep-seated geothermal potential in Japan, the Otake-Hatchobaru geothermal field, a representative fault-controlled hydrothermal system, was selected as a study area. By integrating the existing data we developed a conceptual and a numerical model of the field to represent the extent of the hydrothermal system. The conceptual model indicates that the majority of geothermal fluids discharging fiom the existing wells are supplied by a lateral flow moving above the granitic basement rocks. This interpretation is quantitatively supported by numerical simulation, Accordingly a deep reservoir of around 300°C is believed to exist near the granitic basement along faults which produce conduits for ascending fluids. We need to continue our studies through deep drilling to verify the characteristics of deep reservoirs and to ascertain whether the deep recharge is supplied fiom the granitic basement or not.

1. INTRODUCTION

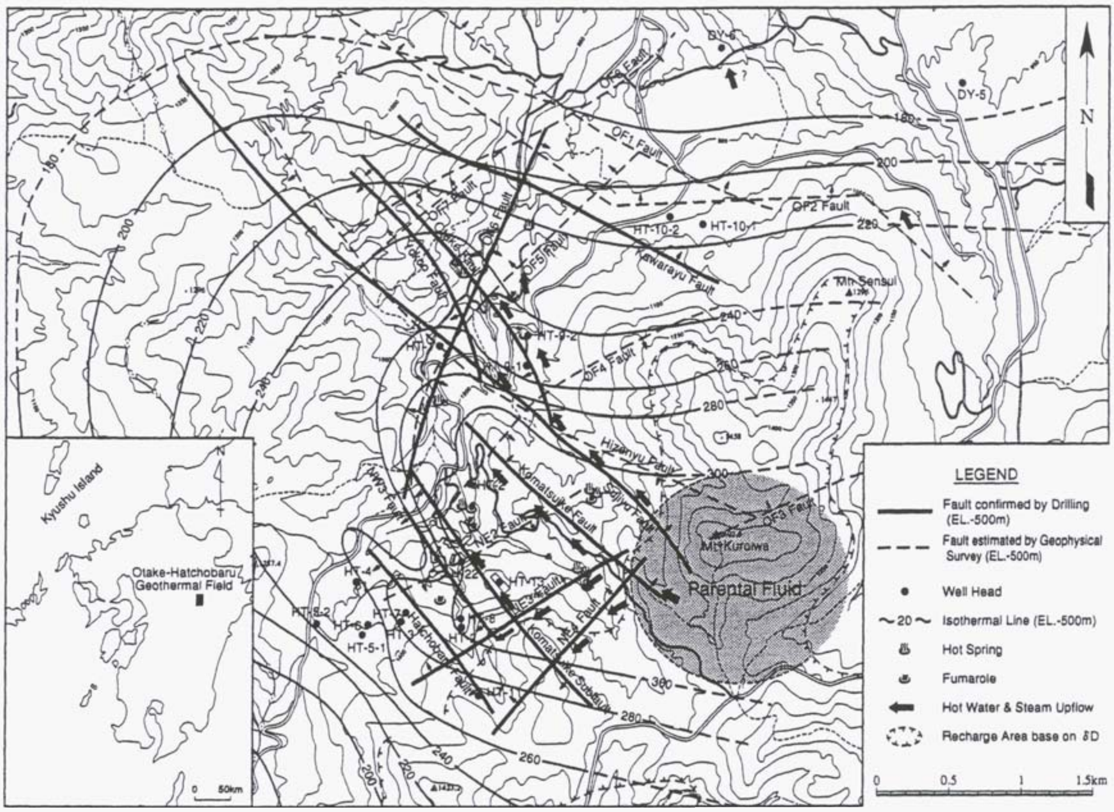
The New Energy and Industrial Technology Development Organization (NEDO) has established the Deep-seated Geothermal Resources (DSGR) Survey Project to evaluate the exploitable potential of deep geothermal reservoirs in Japan. A rough evaluation of the deep geothermal potential without the drilling of deep exploration wells is possible through the estimation of the deep reservoir properties, such as temperature and permeability, based on the interpretation of existing data. In order to make an accurate estimation of the deep reservoir properties, consideration of other influential geothermal factors such as fluid convection and thermal conduction in the hydrothermal system must be made. Numerical simulation is the best tool at hand to study the effects of the deep reservoir properties on the fluid convection and thermal conduction. From this standpoint, we have begun a study (since 1999) to estimate the deep geothermal potential of representative geothermal fields in Japan without drilling deep wells. The study reported here constructs a conceptual model of the deep hydrothermal system, which in turn is followed by numerical simulation to reproduce the extent of geothermal fluids convection. The trials of this project were conducted using the Otake-Hatchobaru geothermal field as a testing field. This is because of its representative fault-controlled reservoir, which is believed to be typical of geothermal systems in Japan. The conceptual model of the region was constructed covering an area of around 60km^2, which includes the Otake-Hatchobaru geothermal field, and goes to a depth of 4000m below sea level. The conceptual model was constructed by integrating existing information to reveal the relationship between the deep geothermal structure and the hydrothermal system, and subsequently, the corresponding numerical model was developed. This paper presents the conceptual model of the Otake-Hatchobaru geothermal field, and then the hydrothermal system reproduced by the numerical simulation is discussed.

2. CONCEPTUAL MODEL

2.1 Deep Geothermal Structure and Fluid Flow

The Otake-Hatchobaru geothermal field is situated in the southwestern margin of the Kuju-Beppu graben, which has a low gravity anomaly zone. This graben is characterised by positive gravity anomalies in some areas, reflecting the existence of horst structures within the area (Tamanyu, 1993). The Otake-Hatchobaru area is located on Kuju's (gravity) positive anomaly zone, which is one of the horsts adjacent to the Shishimuta depression zone. The geologic setting is divided into four units, Kuju volcanic rocks (Middle-Upper Pleistocene), Hohi volcanic rocks (Lower Pleistocene), Usa group (Miocene) and basement rocks (pre-Tertiary), in descending order.

Figure 1 and Figure 2 show the conceptualised patterns of fluid movement and the Otake-Hatchobaru geothermal field, respectively.



The interpretation of isotope data of fluids sampled in this region indicates that the geothermal fluids in the Otake-Hatchobaru field are derived almost entirely fiom meteoric water. The recharge zone is located around the south part of Mt. Kuroiwa. Here, the meteoric water flows downward through the faults and through their related high angle fracture networks associated with the boundary rim of the Shishimuta depression zone. The meteoric water permeating into the deeper zone changes its chemical composition by water-rock interaction and is heated up to about 300°C by a heat source related to the Quaternary volcanism. The heated fluids then migrate upward through the permeable passages associated to the Komatsuike fault (Shimada et al, **1994)** and Sujiyu Fault.

In the Otake area, the thermal fluids migrate upward and northwestward along the Sujiyu and Hizenyu faults. The deep parental fluid is considered to be stored beneath Mt. Kuroiwa, as concluded fiom the analysis of the geologic structure and of the temperature distribution. From this area, the thermal fluids ascend and migrate into the permeable zone related to the NW-SE trending Yoko fault, the Otake fault and through their associated fracture zones to form main reservoirs beneath an altered zone (cap rock) found at a depth of 200-500m below the surface.

In the Hatchobaru area the relationship between the specific enthalpy and chloride concentration of the thermal fluids discharged **ficm many** production wells indicates that these fluids are derived **from** the same parental fluid stored beneath Mt. Kuroiwa which supplies the production at Otake.

The fluids moving towards the production zones of the Hatchobaru area migrate through the fracture zones located along the Komatsuike fault, the NE-3 fault, the NE-4 fault and the Komatsuike sub-fault (**Fujino** and Yamasaki, 1985). These faults seem to penetrate down to the pre-Tertiary basement.

The deep zone beneath the northern slope of Mt. Sensui hosts a relatively small geothermal reservoir along one of the NW-SE trending faults intersected by the well DY-5 **(NEDO, 1985).** Although the deep fluid is believed to migrate from the direction of the Shishimuta depression zone, it is still possible that the supply of fluids is fed by the same parental fluid beneath Mt. Kuroiwa.

Several isotope indices such as B/Cl, As/Cl, and $^{87}Sr/^{86}Sr$ suggest that the deep geothermal fluids ascend through the Tertiary Hohi volcanic rocks and Usa group which overlie the granitic basement.

On the other hand, other geothed reservoirs within the granitic basement were confirmed by wells **2HD-1** and **HT-5-1,** drilled at the southwestern part of the Hatchobaru area. The B/Cl and $^{87}Sr/^{86}Sr$ ratios are quite distinct fiom those of the above-mentioned fluids.

There is enough evidence to assume that the parental fluid of the present production zones in the Otake-Hatchobaru field is stored in deep zones beneath Mt. Kuroiwa. In spite of the existence of a reservoir within the granitic basement, the evidence lead us to believe that the parental fluid supplying the hydrothermal system is a fluid flowing laterally through the Hohi volcanic rocks and Usa group.

2.2 Heat Sources

Based upon the analytical results of petrographic rock dating it is thought that the Kuju volcanic activities, continuing to the present, commenced **700** ka. In this connection, it has been reported (NEDO, 1990) that at a depth of **6.7** km beneath Mt. Kuju, **6km** southeast of the Otake-Hatchobaru area, a pocket of magma at about **950°C** exists, while nearby Mt. Waita, 5km northwest fiom the Otake-Hatchobaru area, a consolidated magma is expected to be located at a depth of 6.7km beneath the surface. Mt. Waita erupted 330 - 700 ka and its residual magma is thought to control the geothermal system in the Oguni area.

In addition, another 600°C heat source is reported to exist 5km beneath Iwoyama volcano. This heat source is 5km southeast of the Otake-Hatchobaru area (Ehara and Hashimoto, 1992).

The geological system in the Otake-Hatchobaru area is supposed to be related to the late Kuju volcanic activity. This activity is represented by the erupted lavas fiom Mt. Goto, Mt. Kuroiwa, Mt. Ryoshi and Mt. Sensui. These lavas have similar faces of rocks and minerals and are dated in 90 - **120 ka** (Kamata, **1997).** Mt. Kuroiwa's eruption was the largest.

From the theoretical point of view, it is presumed that the heat source of the Otake-Hatchobaru area provides the conductive heat to create the present deep temperature conditions. The Curie point in the Otake-Hatchobaru area is estimated to be 6km below sea level where the temperature is estimated in **570°C.** According to the well logging data, the temperature near the top of the pre-Tertiary basement rocks is about 300°C.

The vertical thermal gradient fiom the depth corresponding to the Curie point to the top of the pre-Tertiary basement rock is calculated to be about **54°C/km** in average. This gradient almost coincides with the **4.9°C** per **100m** value estimated **fiom** the temperature surveys carried out in the exploratory well DY-3, which penetrated about 600m into the granitic basement rocks.

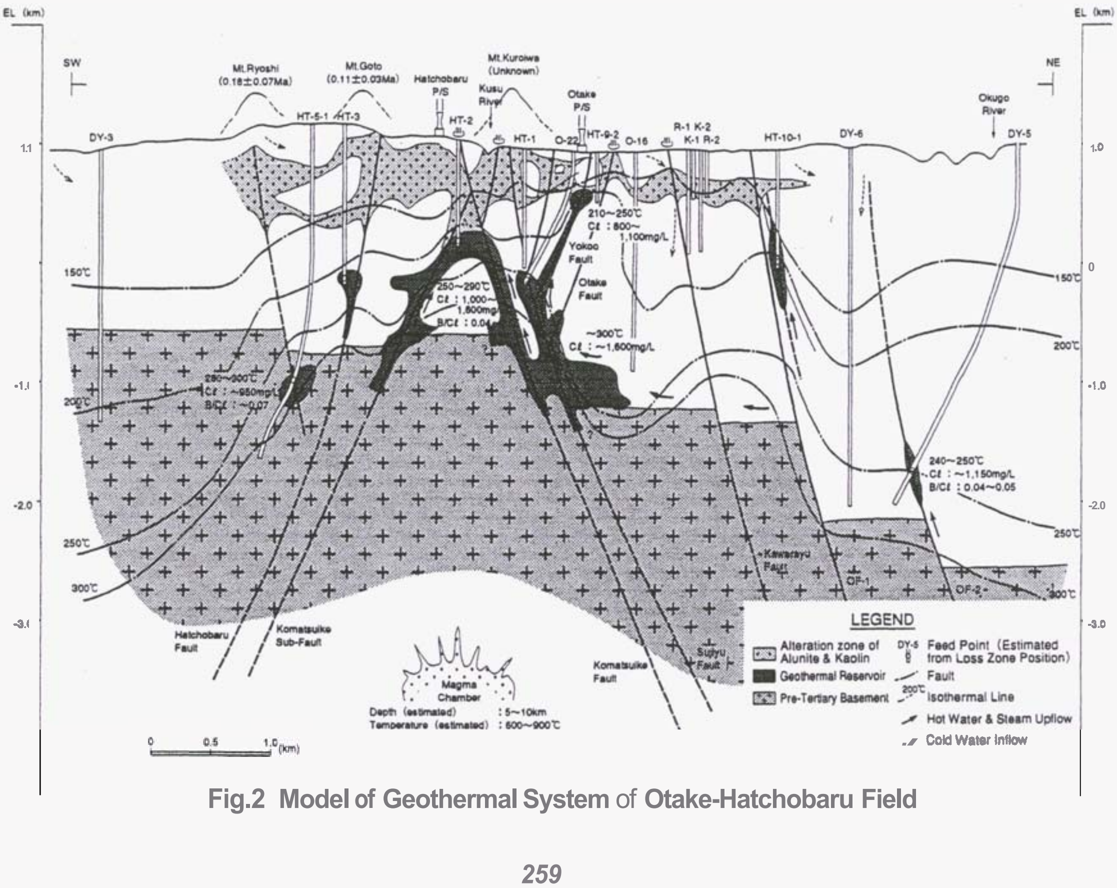


Fig.2 Model of Geothermal System of Otake-Hatchobaru Field

Furthermore, the $\delta^{13}C(CO_2\text{-}CH_4)$ isotopic thermometry of the gases discharged from the wells suggests that fluids at a high temperature of 400-500°C are stored deep beneath the Hatchobaru area. In addition, the isotopic ratio of $\delta^{13}C(CO_2)$ and $\delta^{34}S(H_2S)$ resulting fkom the analysis of discharged gases from wells in the Otake-Hatchobaru area, is close to that fkom Iwoyama volcano and in general close to that in volcanic gases. Therefore we interpret that the gases may be of magmatic origin.

In summary, the heat source of the Otake-Hatchobaru area is considered to correspond to a residual magma chamber beneath Mt. Kuroiwa. Its temperature is presumed to be in the range of 600 – 900°C and its depth is estimated to be 5 - 10 km based on the estimated depths of the heat sources beneath Mt. Kuju and Mt. Waita.

The heat source beneath Mt. Kuroiwa produces enough conductive heat to heat the top of the granitic basement to 300-350°C.

3. NUMERICAL SIMULATION

In order to assure the validity of the conceptual model and to estimate the deep temperature distribution, we carried out numerical simulation by using the simulator TOUGH2 (Pruess, 1991).

3.1 Numerical Model

Figure 3 shows a plan view of the grid design. The numerical model covers 57.7km^2 (7.8×7.4km) centered at the the Otake-Hatchobaru area. The model is surrounded by Mt. Waita, Mt. Mimata, Mt. Ryoushi, and Mt. Kohagi. In the vertical direction, the top and bottom of the numerical model correspond to elevations of about 1100m above sea level and 4000m below sea level respectively.

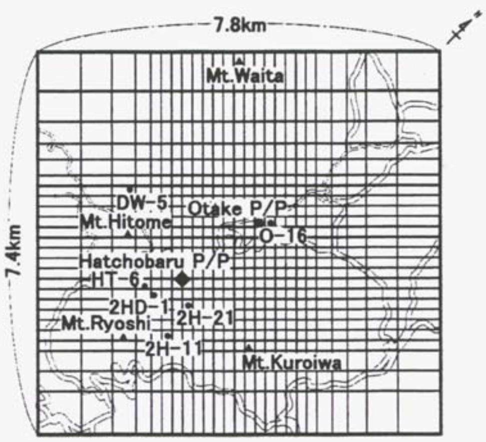


Figure3 Numerical Grid Design(Plain View)

Therefore the thickness of the model is 5100m, which is divided into 13 layers of thicknesses in the range from 250 to 750m. The top two layers are modeled taking the topography into account and the total number of the grid blocks is 8070.

The boundary conditions and distribution of rock properties such as density, porosity, and permeability etc., were initially selected based on the results of well testing and rock-core analysis, and were progressively revised through repeated trial-and-error calibration process until the model could successfully reproduce the actual measured temperature and pressure distributions in the natural state.

We assumed that the main faults associated with the fluid movement penetrate the layers representing the granitic basement rocks in the model. The permeability and porosity for the blocks representing the basement is set to values much smaller than those for the blocks representing the shallower volcanic rocks.

3.2 Simulated Hydrothermal System

The natural state calibration of this region took a total of more than 200 trial-and-error runs until almost satisfactory calibration of measured temperature and pressure were obtained.

Figures 4 and 5 show the calibration of temperature and pressure, respectively. These results indicate that the numerical model can generally explain how the present temperature and pressure distributions of the exploited depths were reached. We are confident that the model can also explain the foxmation of the hydrothermal system in a wide area including the Otake-Hatchobaru geothermal fields.

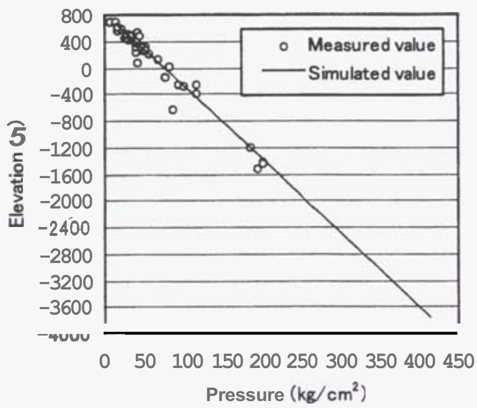


Figure4 Comparison of Measured and Simulated Pressure Profile in Natural State

The natural state model suggests that reservoir fluids are supplied by ascending fluid from the granitic basement rocks and by lateral flow from the south-eastem and north-eastem boundaries of the model. The former is a high temperature fluid of around 300-350°C, supplied along the faults extending into the granitic basement rocks. The flow rate of the ascending fluid along the faults is estimated to be **780 kg/s,** which is around **80%** of the total fluid ascending fiom the granitic basement rocks.

In regard to the lateral flow, it has a temperature below 300°C. This lateral flow moves through two layers of the model (total thickness of 500m) above the layers representing the granitic basement rocks. Its estimated flow rate is around **780kg/s,** similar to that of the ascending flow rate.

Figure 6 shows simulated distributions of the deep water ascending through faults fiom the granitic basement rocks at elevations of 0m, 500m, and 2000m below sea level. These results were obtained using the **EOSl** modules for calculating two **kinds** of water.

As far as the exploited area and depths of the Hatchobaru geothermal field is concerned, the mass fraction of the deep water ascending fiom the granitic basement rocks is below 30%, indicating that more than **70%** of reservoir fluids are supplied by the lateral flow above the granitic basement rocks.

Although a quantitative discussion is still **difficult** because of the non-uniqueness of the results and the unreliability of the numerical model, it seems that the tendency of the simulated fluid flow coincides with the geochemical analysis, which suggests that the majority of the discharged water fiom existing wells is not supplied from granitic basement rocks but from the volcanic rocks.

On the other hand, as far as the whole hydrothermal system of around 60km^2 including the Otake-Hatchobaru geothermal field is concerned, the numerical model suggests that the hydrothermal system is formed by a convection of geothermal fluids. The fluids are supplied almost equally between the ascending flow of deep water from the granitic basement and the lateral flow above the granitic basement. This implies that the supply of deep water **fiom** not only the lateral flow but also **from** the ascending flow is necessary to form such an extensive convection system in this region.

As a future study, we need to drill deep wells to corroborate whether or not there is a deep water ascent fiom the granitic basement rocksand to obtain deep reservoir properties such as permeability, temperature and pressure.

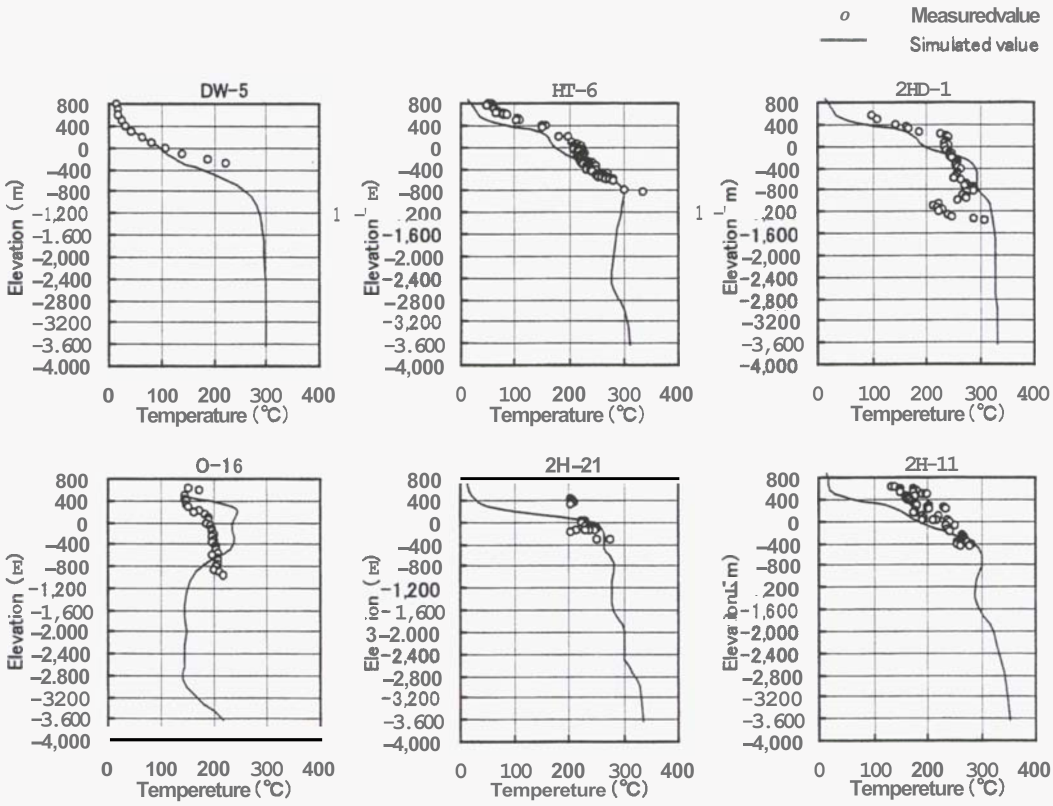


Figure5 Comparison of Measured and Simulated Temperature Profiles of Wells in Natural State

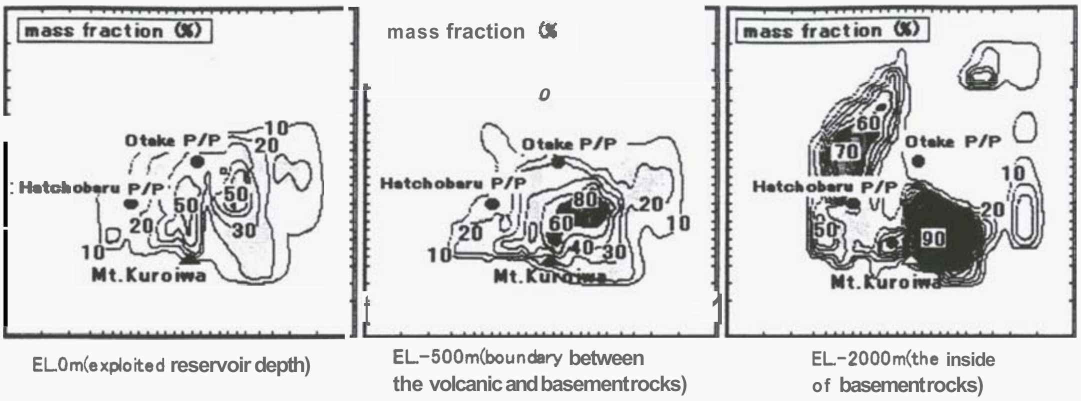


Figure6 Simulated Distributions of Deep Water ascending along Faults from the Granite Basement Rocks

4. CONCLUSIONS

1) The conceptual and numerical models of the hydrothermal system, including the Othake-Hatchobaru geothermal field, are developed to assess the existence of deep exploitable geothermal reservoirs.
2) Based on the chemical analyses such as B/Cl, As/Cl and $^{87}Sr/^{86}Sr$, the majority of geothermal fluids discharging fiom the existing wells of the Otake-Hatchobaru geothermal field appear to be supplied by the lateral flow above the granitic basement rocks. This implies that the contribution of ascending flow fiom the granitic basement rocks to the formation of the Otake-Hatchobaru reservoirs is very limited. This conclusion is also quantitatively supported by the results of numerical simulation.
3) Deep reservoirs of around 300°C are expected to be at the depth near the granitic basement rocks and along the faults and are the dominant pathway for the flows of ascending deep water in this region.
4) When considering the whole hydrothermal system, the numerical model indicates that the supply of deep water fiom the granitic basement rocks as well as the lateral flow above the top of this basement is necessary to form an extensive convection system.
5) We need to further our studies to verify the nature of the deep reservoirs. This could be done by drilling deep exploration wells. We aim to determine the contribution deep water fiom the granitic basement rocks and the formation of the deep reservoirs.

5. ACKNOWLEDGEMENTS

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