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EVALUATION OF DEEP-SEATED GEOTHERMAL RESOURCES IN JAPAN: EMPHASIS ON SIMPLIFIED RESERVOIR MODELS

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ABSTRACT

Deep-seated geothermal resources are found at depths of about 2,000 m or more, and are expected to contribute to the immediate growth of geothermal power generation in Japan. NEDO conducted a survey to determine the characteristics and evaluate the feasibility of utilizing these resources.

In the first phase of the project (FY 1992-1998), a deep exploration well, WD-7, was drilled at Kakkonda. In addition, the following studies were conducted: detailed field survey using the exploration well, research on drilling techniques under conditions of extremely high temperatures, and investigation of the possibility of utilizing deep geothermal fluids. In the second phase of the project (FY 1999-2000), deep-seated geothermal resources in other fields in Japan were evaluated with the numerical simulation technique. Reservoir parameters such as temperature, pressure and permeability were utilized to evaluate the resources in the deep reservoirs. This study aimed to examine various estimation methods of the reservoir parameters and evaluate the potential resources in the deep reservoirs in most of the geothermal' fields in Japan, where no deep exploration wells have been drilled. The exploitation of deep-seated geothermal resources is feasible and highly recommended in order to immediately increase the output of Japanese geothermal power plants.

This article briefly describes evaluation methods and procedures for deep-seated geothermal resources in several fields excluding the Kakkonda field in Japan with emphasis on the simplified reservoir models from geological and reservoir engineering aspects.

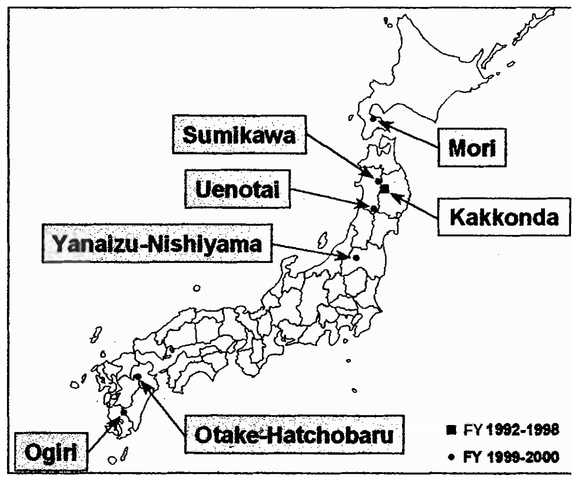


Figure 1. Study areas.

1.0 INTRODUCTION

The Deep-seated Geothermal Resources Survey project was conducted by the New Energy and Industrial Technology Development Organization (NEDO) in order to clarify the overall geothermal system including both deep and shallow reservoirs and to construct guidelines for the development of deep-seated geothermal resources in Japan.

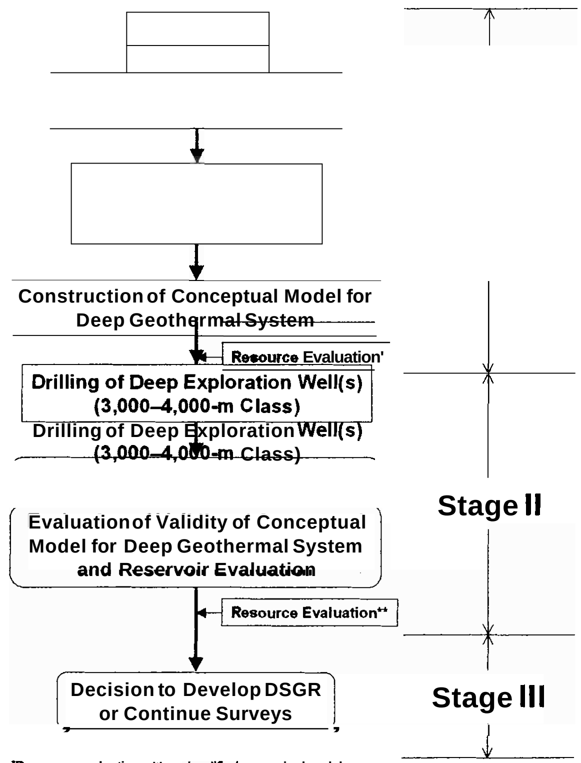
The project started in FY **1992** and was completed in FY 2000. In the first phase of the project (FY **1992-1998**), a deep exploration well, WD-1, was drilled at Kakkonda (Figure **1**). The following studies also were conducted: detailed field surveys using the deep exploration well, research on drilling techniques under conditions of extremely high temperatures, and investigation of the possibility of utilizing deep geothermal fluids. Resources in the deep reservoir in the Kakkonda geothermal field were evaluated with a detailed numerical model using the WD-1 well data.

In the second phase of the project (FY 1999-2000), deep-seated geothermal resources (DSGR) in other fields in Japan were evaluated with the simplified numerical simulation technique. Reservoir parameters such as temperature, pressure and permeability, which were estimated using the existing data (for the shallow reservoirs only), were utilized to evaluate the resources in the deep reservoirs. This study aimed to examine various estimation methods of the reservoir parameters and evaluate the potential resources in the deep reservoir in most of the geothermal fields in Japan, where no deep exploration wells had been drilled. The exploitation of DSGR is feasible and highly recommended in order to immediately increase the output of Japanese geothermal power plants.

This article briefly describes the evaluation methods and procedures for DSGR in several geothermal fields excluding the Kakkonda field in Japan with emphasis on the simplified reservoir models from geological and reservoir engineering aspects.

2.0 GEOTHERMAL FIELD DEVELOPMENT PROCESS

The work-flow process toward the development of DSGR is divided into three stages: Stages I, II and III (Figure 2). Stage I is further subdivided into two sub-stages: Stages I-1 and I-2. The geothermal fields in Japan excluding the Kakkonda field correspond to Stage 1-2 or the first half of Stage II in which no deep-exploration wells have been drilled in the fields. On the other hand, the Kakkonda field corresponds to Stage III because a 30 MWe power plant utilizing steam from the deep geothermal reservoir has been operating since March 1996 and, in addition, a deep exploration well, WD-1, has been drilled. The simplified numerical models described in this article were constructed for resource evaluation of the geothermal fields excluding the Kakkonda field, and a detailed numerical-simulation model, not described in this article, was used for the Kakkonda field.



*Resource evaluation with a simplified numerical model
**Resource evaluation with a detailed numerical model

Figure 2. DSGR **work-flow process.**

3.0 EVALUATION METHODS AND PROCEDURES

An overview of the evaluation of DSGR in Japan is given by Tosha et al. (2001). Detailed methods for estimations of the deep reservoir temperature distributions in the Uenotai geothermal field were described by Shiga et al. (2000). Sato et al. (2000) presents the evaluation of DSGR by using a simplified numerical model in the Uenotai field. Details of conceptual model and estimations of the reservoir parameters and the natural state simulation for the Otake-Hatchobaru geothermal field were described by Momita et al. (2000). Tokita et al. (2002) describes a detailed evaluation of QSGR using a simplified numerical model for the Ogiri geothermal field.

The work-flow process of resource evaluation of deep reservoirs in the geothermal fields excluding the Kakkonda field is shown in Figure 3. This work flow also can be used as the resource evaluation procedure for geothermal fields without any deep exploration well data. A key to successful evaluation of DSGR in the fields without deep exploration well data would

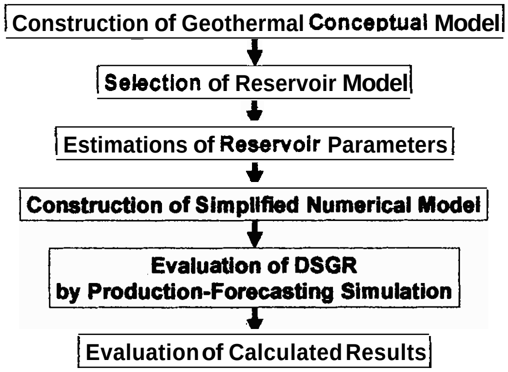


Figure 3. Work-flow process of evaluation of DGSR in the field with no deep exploration wells.

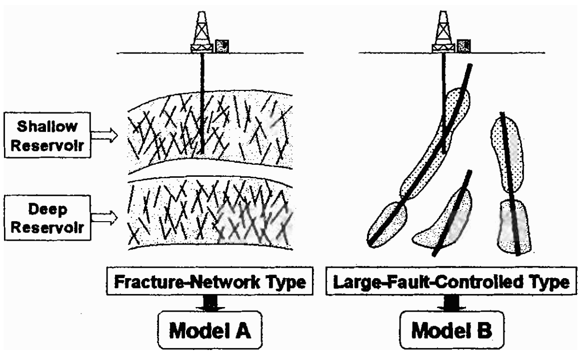


Figure 5. Selection of simplified numerical model based on two types of reservoir models.

be how to estimate appropriate reservoir parameters. In this study, different methods for estimations of reservoir parameters were used tentatively, depending on the reservoir type.

Simplified numerical models were constructed based on two types of reservoir models for deep geothermal systems in Japan. Figure 4 illustrates a conceptual model of the Otake-Hatchobaru field as an example of a conceptual model for a large-fault-controlled type reservoir. Figure 5 shows the selection method of simplified numerical model based on reservoir type. The simplified numerical models used in the study are briefly described as follows.

3.1 Model A

Simplified reservoir model

A reservoir is formed by a fracture-network consisting mainly of small-scale permeable fractures.

Estimations of Reservoir Parameters

Major reservoir parameters were estimated as follows:

- The relaxation method (Tamanyu et al., 1995) combined with an extrapolation method was employed for the subsurface temperature distribution.

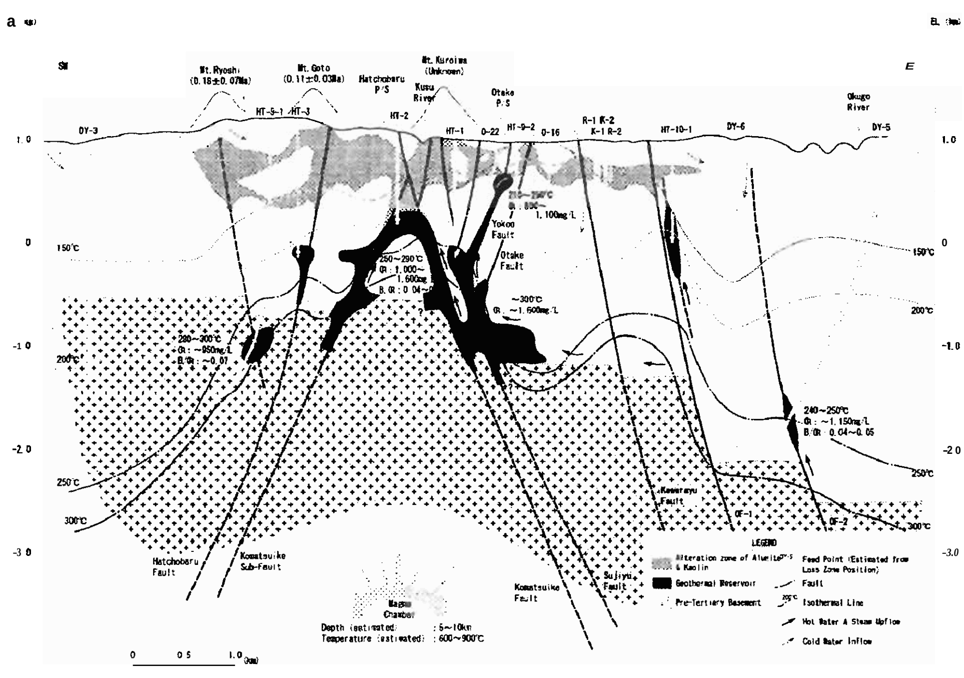


Figure 4. Conceptual model for the Otake-Hatchobaru geothermal field, Kyushu, Japan (cross-sectional view) (modified from Momita et al., 2000).

- A technique for the analysis of the velocity of natural ascending flow (Hanano and Kajiwara, 1999) was used for permeability estimation.

- Basically, the same horizontal extent as the shallow reservoir estimated by the conceptual model was given, and the depth corresponding to a reservoir temperature of 400°C estimated by the stochastic method was used as the depth of the base of the reservoir.

- A linear approximation of an elevation vs. reservoir pressure relationship for the existing data set was used for estimations of deep reservoir pressure distributions.

Model Setting

- Conditions of constant pressure and temperature were applied to the top, bottom and side boundaries.

- Estimated temperature and permeability were given uniformly within a model.

- The horizontal grid size of 250 × 250 m was used for the areas of Uenotai, Sumikawa, Mori and Yanaizu-Nishiyama.

- The model block was divided into three horizontal layers in, and the second layer was defined as the production zone.

Production Scenario

It is assumed that production wells are drilled to a depth of 3,000 m in the second layer of the model and additional production wells are drilled in order to maintain a constant wellhead pressure. Based on this assumption, calculation of output by production-forecasting simulation was made using the simulator TOUGH2 **(Pruess, 1991).**

3.2 Model B

Simplified Reservoir Model

A reservoir is controlled by a large fault(s) having high permeability(ies), and it is assumed that the fault(s) is acting as a flow path(s) of geothermal fluids from deeper zones.

Estimations of Reservoir Parameters

Major reservoir parameters were estimated as follows:

- Logarithmic or involutional approximation to an elevation vs. reservoir temperature relationship for the existing data set was applied for temperature estimation.

- Logarithmic or involutional approximation to an elevation vs. kh (permeability-thickness product or transmissivity) relationship for the existing shallow reservoir data set was applied for kh, then permeability estimation.

- The same areas as those defined for the hydrothermal convection simulation were used as a horizontal reservoir extent.

- The same technique as that of Model A was used for pressure estimation.

Model Setting

- Barrier boundaries for the top and part of the sides and bottom were assumed.

- Constant pressure and temperature for the side boundaries of the model were assumed.

- Two conditions of deep geothermal-fluid supply were considered: **(1)** conditions of a constant flow rate, and (2) conditions of constant pressure and temperature in an area of geothermal-fluid supply.

- The horizontal grids used in the hydrothermal convection simulation, ranging from 200 × 200 m to 800 × 800 m in the Otake-Hatchobaru area and from 250 × 250 m to 1500 × 2000 m in the Ogiri area, respectively, also were used for the simplified numerical simulations.

- A single-layer model for both the Otake-Hatchobaru and Ogiri areas was used.

Pmduction Scenario

It is assumed that production wells are drilled to a deep reservoir, and in addition, the following two cases are assumed: **(1)** output by steam production from all the wells emplaced in the field is stabilized; and (2) additional production wells are drilled in order to maintain a constant output. Calculation of an output by production-forecasting simulation using the simulator TOUGH2 was made for the above two cases, respectively.

Field	Mori	Sumikawa	Uenotai	Yanaizu-Nishiyama	Otake	Hatchobaru	Ogiri
Resources*	21.0	21.6	21.4	21.0	3.6–3.7	1.0–1.1	0.6–1.5
Decline Rate (%/year)	4	4	3	4	5	5	5
Model Type	A	A	A	A	B	B	B

4.0 RESERVOIR TYPING FOR RESOURCE EVALUATION

Typing of reservoir models for simplified numerical simulation was reviewed from geological and reservoir engineering aspects. Based on this review, we proposed two types of reservoir models for resource evaluation.

Model A is characterized by a fracture-network type reservoir, consisting mainly of small-scale permeable fractures. This reservoir type can be treated as a porous-type model from the viewpoint of reservoir engineering. If the size of a reservoir unit is large enough compared to the average size of minimum fracturenetwork units, or blocks bounded by fractures, the model can be regarded as a porous-type reservoir. A volumetric method can be applied to this model for resource evatuation.

Model B is characterized by a large-fault-controlled type reservoir, with continuous supply of deep geothermal fluids along the fault(s) from deeper zone(s). This indicates that the reservoir geometry is strongly dependent on the configurations and spatial distributions of the fault(s). Therefore, the reservoir geometry in this resetvoir type is important for constructing the numerical simulation model. Actual well data show that flow rate per welt is relatively high and the production behavior suggests that productive fault(s) have predominantly high permeabilities.

Available data indicate that the geothermal reservoirs in Japan are classified roughly into the fracture-network and large-fault-controlled types from the viewpoint of resource evaluation, and the former is dominantly distributed in the Tohoku/Hokkaido areas and the latter in the Kyushu area. This may reflect the difference in the regional tectonic stress fields between the Tohoku/Hokkaido and the Kyushu areas. At present the geothermal fields in the Tohoku/Hokkaido areas are in compressional stress fields, and on the other hand, those in the Kyushu area are in extensional stress fields. For example, an analysis of microearthquake data acquired in the Kakkonda area shows that the stress field in the area has a regional compressional stress axis in the ENE-WSW direction.

5.0 RESULTS OF RESOURCE EVALUATION

The results of resource evaluation of the geothermal fields using the simplified numerical models are summarized in Table 1. Resources are shown as a ratio of the estimated output for the deep reservoir to that produced from the shallow reservoir. Tosha et al. (2001) also summarized the results of the evaluation of OSGR in Japan.

The results indicate that the deep reservoirs in the geothermal fields have potential resources of about 1.5 times on average greater than those of the shallow reservoirs developed in Japan. The results encourage the development of deep-seated geothermal resources in Japan.

6.0 CONCLUSIONS

- Resource evaluation of the potential deep geothermal reservoirs in several geothermal fields in Japan, where no deep exploration wells we had been drilled, was successfully conducted by using either of simplified Model A or B, applied to the fracture-network type and large-faultantrolled type reservoirs, respectively.

- The two types of reservoir models proposed in this article are based on the differences in reservoir geology and production characteristics.

- The characteristics of distribution of the fracture-network and large-fault-controlled reservoir types may reflect the difference in the present-day regional tectonic stress fields between the Tohoku/Hokkaido and Kyushu areas. The geothermal fields in the Tohoku/Hokkaido areas are in compressional stress fields, and those in the Kyushu area are in extensional stress fields.

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