EVOLUTION HISTORY OF THE KAKKONDA MAGMA-HYDROTHERMAL SYSTEM, JAPAN, ESTIMATED THROUGH SIMPLIFIED-MODEL NUMERICAL SIMULATIONS

Hiroshi Shigeno

1-1-3 Higashi, Tsukuba, Ibaraki 305-8567, Japan
e-mail: shigeno@gsj.go.jp

ABSTRACT
At the Kakkonda geothermal area, Japan, a large Quaternary granitic body is distributed below ca. 2.5 km depth from the surface, associating with thick high-temperature contact metamorphic zones in the overlying formations, and a meteoric-water-embibinated type hydrothermal system is developed at present time. During the 'Deep-seated Geothermal Resources Survey', WD-1a well was drilled to 3729 m depth, and a thermal conduction zone with a maximum temperature over 500°C was observed in the Quaternary granitic body.

Evolution history of the Kakkonda geothermal system was analyzed by the numerical simulation method based on the simplified onedimensional transient thermal conduction models, in which high 'extended thermal conductivity' was assumed for geothermal reservoirs (Shigeno, 1999a). The time-space temperature distribution data obtained from the WD-1a well could be explained by the following dynamic environment model (KR1 model): (1) At first, the thick contact metamorphic zones were produced through heat storage by thermal conduction from the magma chamber emplaced probably ca. 0.20 Ma; (2) Later (e.g., 0.03 Ma), reservoir formation caused the present convective temperature profile with the high conductive temperature gradient in the cooling Quaternary granitic body. A modified three-stage scenario (KM2 model) that assumed contribution of magmatic fluid convection in the granitic body for the first stage improved fitting of the observed and simulated temperature profiles for the contact metamorphism.

OUTLINE OF KAKKONDA GEOTHERMAL SYSTEM AND WD-1A WELL

In the Kakkonda area, the Quaternary granitic body was emplaced in pre-Neogene formations overlain by Neogene volcanic and sedimentary formations. The time of the magma emplacement has been controversial, though most K-Ar ages obtained from the minerals in the granitic rocks were ca. 0.20 Ma (Kanisawa et al., 1994; Doi et al., 1998). The above formations were thickly affected by high-temperature contact metamorphism of the granitic body. However, the two semi-continuous hot-water type geothermal reservoirs, whose temperatures range ca. 220°C to 380°C from shallow to deep levels, are presently developed in these formations and the uppermost part of the granitic body (e.g., Hanano (1998)). The Kakkonda I (50 MWe) and II (30 MWe) geothermal power plants have been operating in this area since 1978 and 1996, respectively (e.g., Takanoashi (1999)).
The WD-1a well, drilled at the north-westernmost part of the exploited geothermal area, showed a convective temperature profile above 3.1 km depth, including the uppermost part of the granitic body, but a steep conductive profile below 3.1 km depth, reaching 500°C at the bottom end (3729 m depth) (Figs. 1 and 2). However, the mineral isograds of the contact metamorphism in the above formations suggest that the maximum temperatures increasing with the depths were much higher (e.g., 590°C to 670°C at 2.5 km depth) in the past (Fig. 2). Fluid inclusion analysis for the WD-1a well (Komatsu et al., 1998) revealed that the granitic body is characterized by abundant high-temperature (350°-650°C) highly-saline (30-50 wt.%) polyphase type inclusions, and vapor-rich type inclusions suggesting contributions of magmatic fluids and their phase separations. The sample waters collected from the deepest part of the WD-1a well indicated that the magmatic fluids have partly remained in the consolidated granitic rocks (Kasai et al., 1998). On the other hand, the above overlying formations are dominated by liquid-rich type fluid inclusions (ca. 220°-400°C, low salinity) being consistent with the present reservoir hot-waters of meteoric water origin (Komatsu et al., 1998).
MODELING AND SIMULATION METHOD

Shigeno (1999a) proposed a vertical one-dimensional transient thermal conduction model for better understanding, through visualizing, diversities of macroscopic features of magma (igneous)-hydrothermal systems, especially for deep geothermal environments to explore and exploit. In the simplified modeling, the 'extended thermal conductivity' (Kext) was defined through the following equations (1) to (4), based on one-dimensional steady-state thermal convection layer with constant top and bottom boundary temperatures:

\[ H_{tot} = \text{Nu} \cdot H_{cond} \]  
\[ H_{cond} = K_m (T_L - T_U) / L \]  
\[ H_{tot} = K_{ext} (T_L - T_U) / L \]  
\[ K_{ext} = \text{Nu} \cdot K_m \]

where \( H_{tot}, \text{Nu}, H_{cond}, K_m, T_L, T_U, \) and \( L \) are total heat flow by conduction and convection (W), Nusselt Number (-), heat flow by conduction (W), thermal conductivity of the layer (W/m-K), the bottom and top boundary temperatures (K), and thickness of the layer (m), respectively.

The above modeling method was applied to the Kakkonda geothermal system in order to analyze its evolution history. It was assumed that the magma emplacement instantly occurred 0.2 Ma, and macroscopic one-dimensional features of the Kakkonda system through the history could be represented by the data obtained from the WD-1a well.

Fig. 3 shows the generalized conceptual and mathematical model for the Kakkonda geothermal system used for the simulation analysis in this study. Major points were as follows (Shigeno, 1999a, 1999b):

1. It was a vertical one-dimensional transient thermal conduction model using the 'extended thermal conductivity.' Simulation depth and time were from the surface to 20 km depth, and from the instant magma emplacement to 400,000 years later, respectively.

2. Distribution of averaged geothermal units (magma chamber, geothermal reservoir, or non-magma-and-non-reservoir) was assumed for each depth. Fluid phases were included in them.

3. Not only static, but also dynamic environment models (scenarios: e.g., temporal change from the non-magma-and-non-reservoir to the reservoir) were used.

4. Depths of the top and bottom of the magma chamber were assumed as constants (2.8 and 10.8 km, respectively). Those of the reservoirs were assumed as parameters.

5. It was assumed that the reservoirs (and partly the magma chamber) had high Kext values, mostly ten times higher than that of the non-magma-and-non-reservoir (2.5 W/m-K). Heat capacity and density of the above geothermal units were assumed as constants: 1.0 kJ/kg-K and 2,700 kg/m³, respectively.

6. Boundary and initial conditions for temperature distributions were assumed as shown in Fig. 3. Also, latent heat of magma consolidation (at 900°C, constant) was assumed as shown in Fig. 3.

Using the above models, forward numerical simulations based on simple explicit difference equations were conducted. Refer to Shigeno (1999a, 1999b) for details.

RESULTS AND DISCUSSION

Static-Environment Model Analysis

Fig. 4 shows simulation results for three cases, K1, K3 and K5 among other cases (Shigeno, 1999b), based on static environment models. As a natural conclusion,
these simple static models could not explain the past metamorphic and present hydrothermal temperature distributions obtained from the WD-la well.

The K1 model assumed simply that the reservoirs have never developed and thermal conduction has minimized through the time. In this case, the calculated maximum temperatures for the contact metamorphism increasing with the depths were much higher than those calculated by the following K3 and K5 models. However, the calculated maximum temperatures by the K1 model were clearly lower than the reported isograd temperatures (e.g., ca. 500°C vs. ca. 630°C at 2.5 km depth). On the other hand, the calculated temperatures increasing linearly with the depths for the assumed present time (200,000 years after the magma emplacement) by the K1 model were much higher than the observed reservoir temperatures (e.g., ca. 450°C vs. ca. 360°C at 2.5 km depth).

The K3 model, being quite opposite to the K1 model, assumed that one reservoir, extending from 0.5 to 2.8 km depth, from near the surface to the top of the magma chamber, has existed through the time. The assumed Kext value of the reservoir was 25.0 W/m-K. In this case, the calculated maximum temperatures increasing with the depths were very low (e.g., ca. 330°C at 2.5 km depth). Also, the calculated temperatures for the present reservoirs by the K3 model were much lower than the observed temperatures.

The K5 model, which is a slightly complicated two-layered reservoir model modified from the K3 model, assumed that shallow and deep reservoirs have existed through the time, and have kept different Kext values, 25.0 and 7.5 W/m-K, respectively. In this case, the calculated maximum temperatures for the deep reservoirs (e.g., ca. 400°C at 2.5 km depth) were in between those by the K1 and K3 models. Also, the calculated temperatures for the present reservoirs by the K5 model were much lower than the observed temperatures.

**Dynamic-Environment Model Analysis**

Figs. 5 and 6 show simulation results and conditions for two cases, KRI and KM2 among other cases (Shigeno, 1999b), based on dynamic environment models (scenarios). The KRI and KM2 models gave the optimal results to explain the thermal history data from the WD-la well in the tested cases.

The KRI model that assumed dominance of a thermal conduction system (like the K1 model) at the first stage, and development of a hydrothermal system at the present reservoir depths (0.5 to 3.1 km depth) at the later stage (ca. 0.03 Ma to later) (Fig. 6, left) could give fairly reasonable simulation results (Fig. 5, top) consistent with the thermal history data from the WD-la well (Fig. 2). However, the calculated maximum temperatures increasing with the depths were 50°-150°C lower than the reported isograd temperatures shown in Fig. 2.

The KM2 model, which modified the KRI model, assumed higher Kext value (7.5 W/m-K) for the magma chamber and the shallow part of the consolidated granitic body at the early stage (for 100,000 years...
Fig. 5 Simulation results for evolution history of the Kakkonda geothermal system, based on the one-dimensional transient thermal conduction models (2A). KRI (top) and KM2 (bottom) are based on dynamic environment models. (A) Temperature contour lines (50°C intervals) on time-depth planes (down to 4 km depth). (B) Temperature-depth profiles changing with time (50,000 year intervals) up to 400,000 years after the magma emplacement (down to 4 km depth). (C) Temperature-depth profiles changing with time (the same intervals as in (B)) down to 20 km depth. Refer to Fig. 6 for temporal changes of distributions of the 'extended thermal conductivity'. See Fig. 2, Fig. 3 and the text.

Fig. 6 Simulation results for evolution history of the Kakkonda geothermal system, based on the one-dimensional transient thermal conduction models (2B). Scenarios for the dynamic environment models, KRI (left) and KM2 (right): Distributions of the 'extended thermal conductivity' changed with time are shown on time-depth planes (down to 20 km depth). See Fig. 5 for the simulation results for temperature distributions.
Fig. 7 Comparisons of simulation results for evolution history of the Kakkonda geothermal system, based on the one-dimensional transient thermal conduction models. Temporal changes of the temperatures at six depths (1.5 to 4.0 km depth from the surface), calculated based on K1, K3, KR1, and KM2 models are shown. Assumed present time is 200,000 years after the instant magma emplacement (0y). Refer to Fig. 2 for the present temperature profile obtained by well logging, and the past maximum temperature profile estimated by metamorphic minerals for the WD-la well. See Figs. 3, 4, 5 and 6, and the text.

After the magma emplacement (Fig 6, right). This modification of the KM2 model is consistent with the results of the fluid inclusion study for the WD-la well (Komatsu et al., 1998). The KM2 model could improve the discrepancies between the simulated and reported maximum temperatures for the contact metamorphism increasing with the depths (Fig. 5, bottom).

Some more simulation analysis was conducted based on other dynamic environment models, including reservoir formation through hydrofracturing by metamorphic fluid release depending on temperature changes (e.g. Muraoka et al. (1998)). However, the results were not consistent enough with the reported temperature data from the WD-la well (Shigeno, 1999b).

Optimal Model

Fig. 7 compares the above simulation results based on the static and dynamic environment models (K1 and K2; KR1 and KM2). The KM2 model is so far the optimal model that could produce the outline of the thermal history for the Kakkonda magma (igneous)-hydrothermal system (Shigeno, 1999b).

For better understanding the evolution history of the Kakkonda geothermal system, where the actual times of the magma emplacement and the reservoir formation are not clear yet, the following two points obtained by extending considerations on the above results are probably very important.
(1) The cooling rate of the reservoirs developed at the later stage is probably very fast. The reason for this is the combinations of the shallow bottom depth of the reservoir cap rock and the shallow top depth of the conductive heat source (the granitic body). The reservoirs can probably keep high temperature only for a short period (e.g. for 50,000 to 100,000 years).

(2) The cooling rate of the conductive system developed at the early stage (the metamorphic system) was probably very slow due to slow thermal conduction. Hence, interpretations for the duration of the early stage can be very flexible (e.g. 100,000 to 300,000 years long.)

**Remaining Problems and Future Studies**

The above optimal model and simulation results were based on the very simple assumptions and limited data obtained mainly from the WD-1a well. Hence, there remained many problems to be solved in future. These could be summarized as follows:

(1) The modeling method of this study has some flexibility to cope with uncertainties existing in the reported estimation values. Improved optimal models and simulation results might be obtained by adjusting the parameter values of the KR1 and KM2 models, when better estimation values (e.g. much younger or older ages for the magma emplacement, and lower or higher metamorphic temperature distributions (e.g. Takeno et al. (1999))) were obtained.

(2) Applicability of the above one-dimensional assumption to the Kakkonda geothermal system is a critical problem (Shigeno, 1999a, 1999b). Estimations of the latest studies seem to be more supportive for this assumption than those of previous studies (e.g. Doi et al. (1998)), though large uncertainties remain. The latest microearthquake studies (e.g. Tosha and Nishi (1999)) suggested that the distribution of the Quaternary granitic body is much wider (e.g. 8 x 8 km), and the Kakkonda hydrothermal system (ca. 2 x 4 km) is located not on the south-westernmost marginal part but rather near the central part of the granitic body.

(3) Another important problem to be solved is formation mechanism of the present hydrothermal system (e.g. Murooka et al. (1998), Doi et al. (1998), Shigeno (1999b)). The latest K-Ar dating study for alteration minerals (Akatsuka et al., 1999) indicated that hydrothermal activities occurred not only near present time, but also ca. 5 Ma, probably by the emplacement of the Tongonotaki Dacite (Fig. 1, TD). This suggests that series of processes have repeatedly occurred in and around the Kakkonda area as follows:

- Emplacement of magma chamber, development of thermal conduction system (contact metamorphism), formation of convection system (hydrothermal alteration), and development of self-sealed cold system. Groundwater hydrology regulated by rivers (presently the Kakkonda river system) that have deeply ended the uplifting Backbone Range, the volcanic front area of the Northeast Japan Arc, may have been the major cause of the repeated formations of the hydrothermal systems.

(4) Actual evolution history of the Kakkonda geothermal system should have been much more complicated especially for history of the magmatic processes at the depth. This study might be too simple, especially in the sense, but could be an introduction or reference for more advanced studies in future.

**SUMMARY**

At the Kakkonda geothermal area, a large Quaternary granitic body is distributed below ca. 2.5 km depth from the surface, associating with high-temperature contact metamorphic zones over 1 km thick in the overlying pre-Neogene and Neogene formations. A meteoric-water-dominated type hydrothermal system developed at present time has been exploited for geothermal power generation by two stations with a total capacity of 80 MWe. During the ‘Deep-seated Geothermal Resources Survey’ in this area, an exploration well, WD-1a, was drilled to 3729 m depth in 1995, and a thermal conduction zone with a maximum temperature over 500°C was observed at the deepest part of the well.

Evolution history of the Kakkonda geothermal system was analyzed, in a semi-quantitative manner, by the numerical simulation method based on the simplified one-dimensional transient thermal conduction models, in which high ‘extended thermal conductivity’ \( (K_{ext}) \) was assumed for geothermal reservoirs (Shigeno, 1999a). The timespace temperature distribution data obtained from the WD-1a well could be explained by the following dynamic environment model (two-stage scenario, KR1 model): (1) At first, the thick contact metamorphic zones (ca. 350°-650°C at 1.5 to 2.8 km depth) were produced through heat storage by thermal conduction from the magma chamber (top depth 2.8 km deep) emplaced probably ca. 0.20 Ma; (2) Later (e.g. 0.03 Ma), reservoir formation caused the present convective temperature profile (ca. 220°-380°C at 0.5 to 3.1 km depth) with the high conductive temperature gradient below 3.1 km depth in the cooling Quaternary granitic body. A modified three-stage scenario (KM2 model) that assumed contribution of magmatic fluid convection, which enhanced heat transport from the magma chamber to the overlying formations, for the first stage improved fitting of the observed and...
simulated temperature profiles for the contact metamorphism.

ACKNOWLEDGMENTS

I thank to the group members of the 'Data Analyses and Evaluations for the Deepseated Geothermal Resources Survey' at the Geological Survey of Japan, for their cooperation and discussions. This study was conducted with financial supports by the office of the New Sunshine Program, AIST, METI, and through cooperation with NEDO, JMC, GEO-E and GERD. I am grateful to them. Also, I would like to thank the members of the committee and sub-committees for this NEDO project for their discussions.

REFERENCES


