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

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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-cbminated type hydrothermal system is developedat 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 dataobtainedfrom 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 modfied 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.

INTRODUCTION

Deep reservoirs at exploited geothermal areas have become very important targets for power generation developments in Japan, where promising geothermal areas for the exploitation have been very limited by distributions of numerous National Parks and hot-spring resort areas (*e.g.* Shigeno (1995)). Hence, the 'Deep-seated Geothermal Resources Survey' was started by MITI and NEDO in 1992, and a deep exploration well, WD-la, was drilled at the Kakkonch geothermal area, Iwate Prefecture, Northeast Japan. As a result, it revealed one type of deep geothermal environments in and around a young igneous body emplaced to shallow levels, reaching 500°C at 3729 m depth in 1995 (Uchida et *al.*, 19%; Muraoka et *al.*, 1998; Doi et al., 1998).

Cooperating with NEDO for the project, a geothermal group at the Geological Survey of Japan has been studying the deep geothermal systems for their modeling, exploration methods, reservoir evaluations, and resources assessments. This paper shows a study result for evolution history of the Kakkonch magma (igneous)-hydrothermal system estimated through simplified modeling and numerical simulation methods using the logging and analysisdataofthe WD-1a well.

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 volcanicand sedimentaryformations (Fig. 1). 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 *ul.*, 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" to 380°C from shallow to deep levels, are presently developedin these formations and the uppermost part of the granitic body (*e.g.* Hanano (1998)). The Kakkonda I (50 MWe) and11 (30 MWe) geothermal power plants have been operating in this areasince 1978 and 1996, respectively (*e.g.* Takanohashi (1999)).

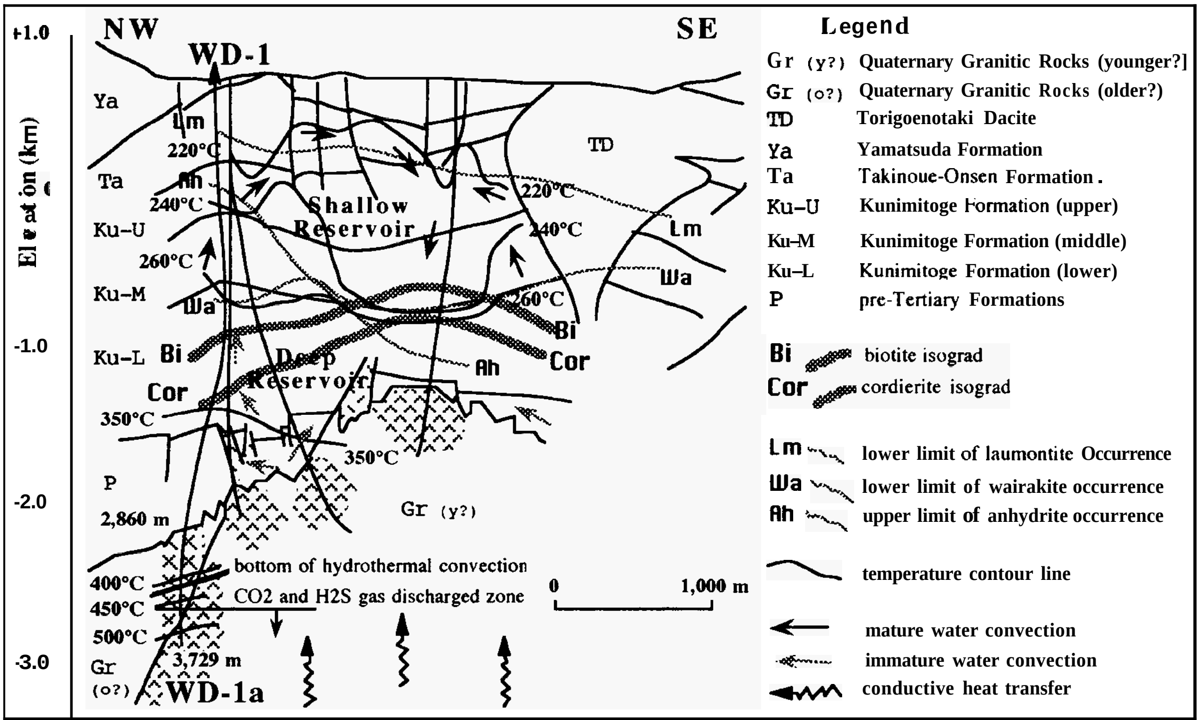


Fig. 1 Cross section and conceptual model of magma (igneous)-hydrothermal system at the Kakkonda geothermal area (modified from Uchida et al. (1996)). Distributions of geologic units, metamorphic minerals, alteration minerals and temperatures are shown with models of geothermal units, transport modes of heat and fluids, and others.

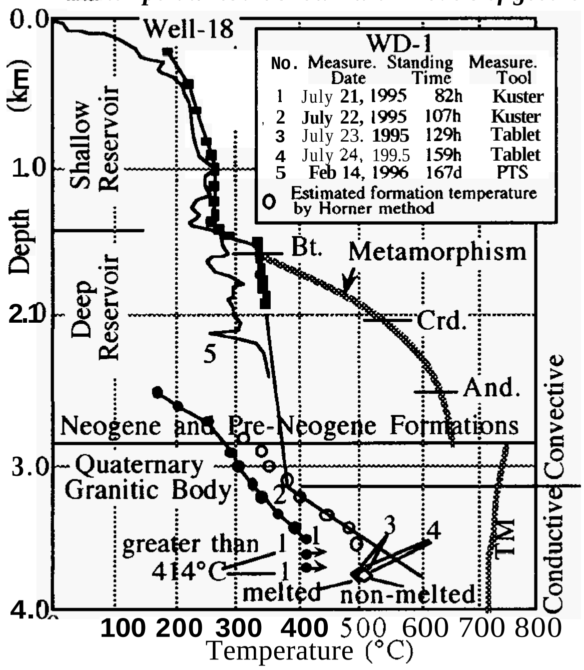


Fig. 2 Present temperature profile obtained by logging, and past maximum temperature profile estimated by metamorphic minerals for the WD-la well in the Kakkonda area (modified from Sasaki et al. (1998)). Bt., Crd., and And. are isograds for biotite, cordierite and andalusite, respectively, and TM is ternary minimum curve of granitic melt.

The WD-la well, drilled at the north-westemmost 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° to 670°C at 2.5 km depth) in the past (Fig. 2).

Fluid inclusion analysis for the WD-la 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-la well indicated that the magmatic fluids have partly remained in the consolidated granitic rocks (Kasai *etal.*, 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).

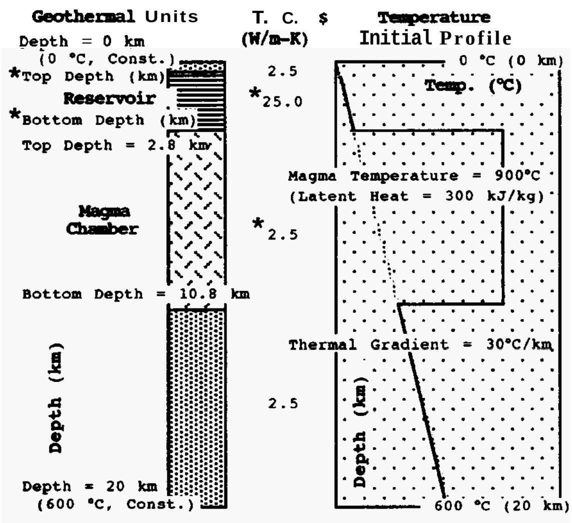
MODELING AND SIMULATION METHOD

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

$$Htot = Nu\ Hcond \quad (1)$$
$$Hcond = Km\ (TL - TU)\ /\ L \quad (2)$$
$$Htot = Kext\ (TL - TU)\ /\ L \quad (3)$$
$$Kext = Nu\ Km \quad (4)$$

where ***Htot, Nu, Hcond, Knt, TL, TU,*** and ***L*** **are** total heat flow by conduction and convection (W), Nusset 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



$ 'Extended Thermal Conductivity'

***Fig. 3** One-dimensional transient thermal conduction modelfor simulating evolution history ofmagma (igneous)-hydrothermal system at the Kakkonda area. 'Extendedthermal conductivity'was applied to geothermal reservoirs, andpartlyto magmaand its consolidated rocks (see the text). * indicates parameters whose values were changed according to concrete simulation models (modified from Shigeno (1999a, 1999b)).*

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 usedfor the simulation analysis in this study. Major points were as follows (Shigeno, 1999a, 1999b):

(1) It was a vertical one-dmensional 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). Heatcapacity anddensity of the above geothermal units wereassumed as constants: 1.0 kJ/kg-K and 2,700 kg/m^3, respectively.

(6) Boundary and initial conditions for temperature distributions were assumed as shown in Fig. 3. Also, latent heat of magmaconsolidation (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 Analvsis

Fig. 4 shows simulation results forthreecases, K1, K3 and K5 among other cases (Shigeno, 1999b), basedon static environment models. As a natural conclusion,

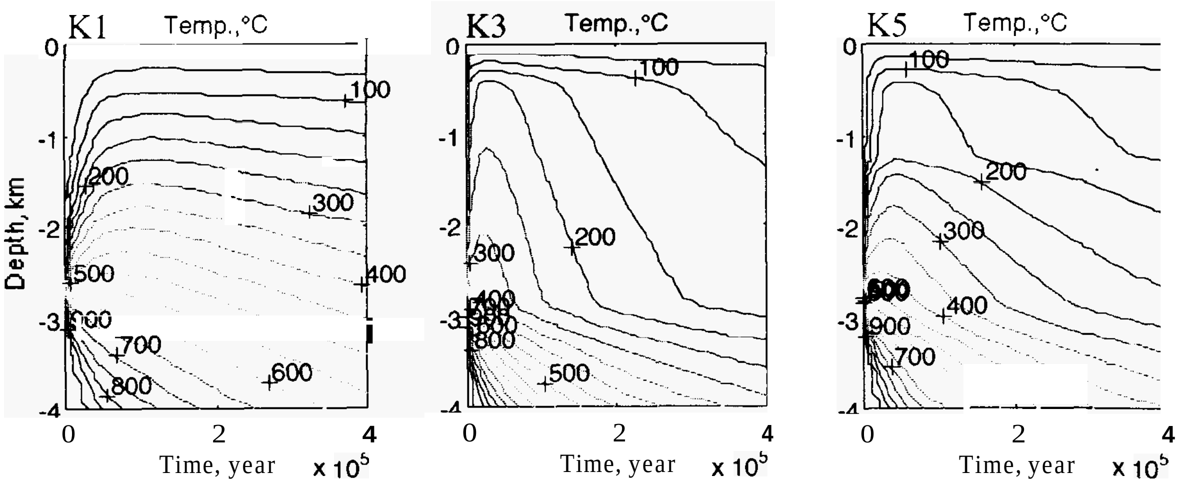


Fig. 4 Simulation resultsforevolution history of the Kakkonda geothermalsystem, based on the one-dimensional transient thermal conductionmodels (1). K1, K3 and K5 are based on static environmentmodels. Temperuturecontourlines (50°C intervals) were drawn *on time-depth planes (down to 4 km depth). See Fig. 2, Fig. 3* and *the text.*

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 Qminated 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 higherthan 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 reservoir levels (*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.

Dvnamic-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 tasted 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 calculate 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

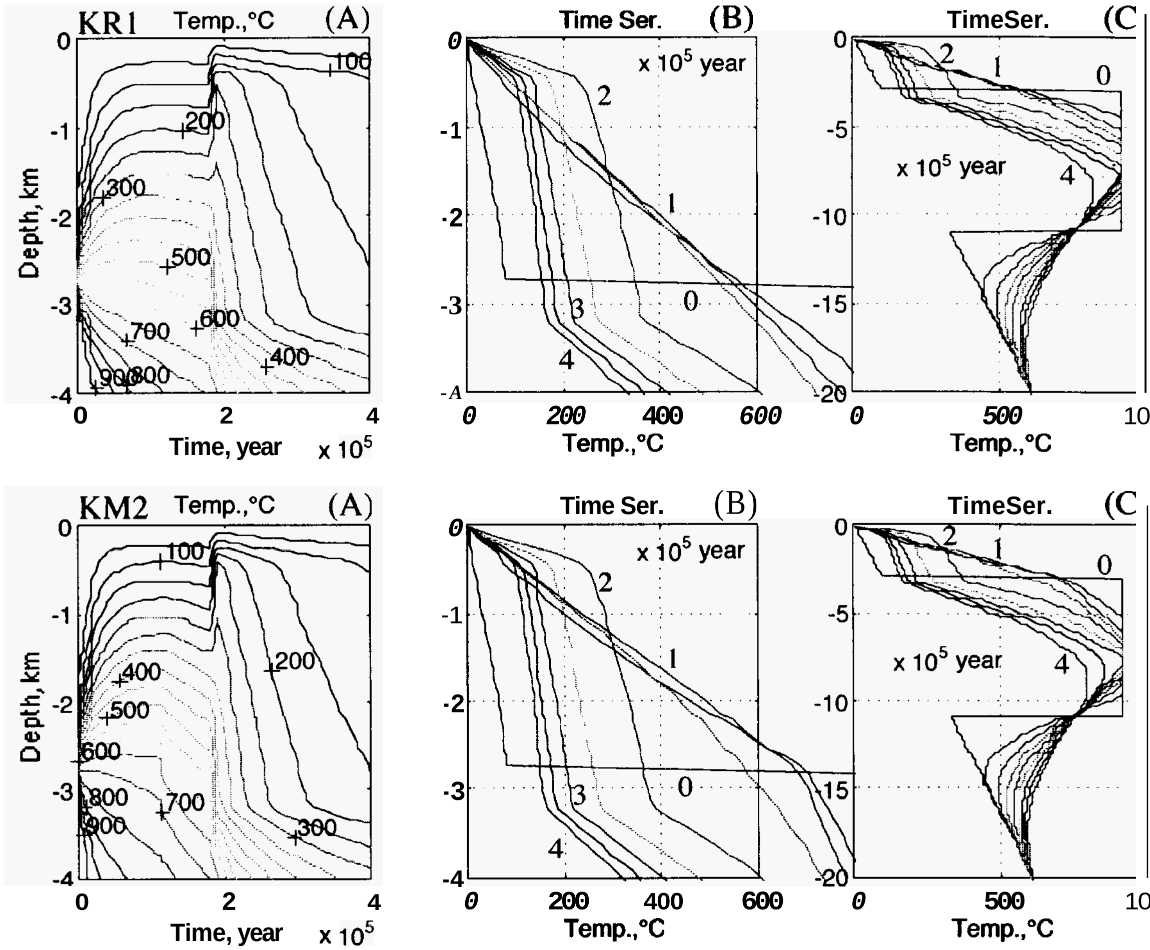
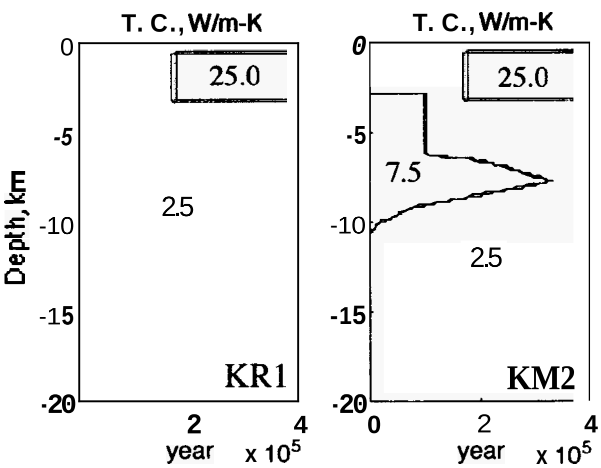


*Fig. **5** Simulation results for evolution history of the Kakkonda geothermal system, based on the one-dimensional transient thermal conduction models (2A). KRI (top) and KM2 (bottom) are based on dynamic environment models. (A) Temperature contour lines (50°C intervals) on time-depth planes (down 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.*

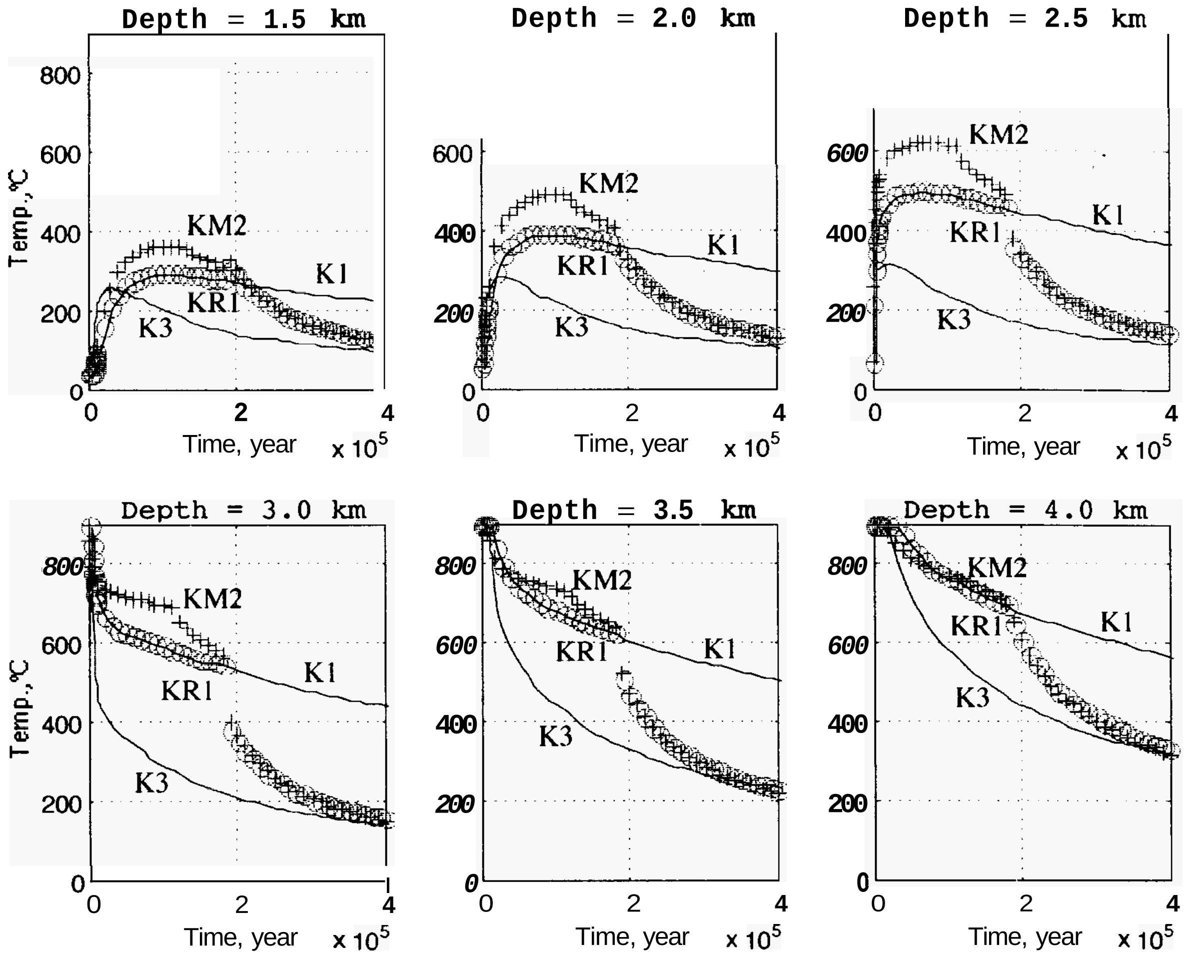


Fig. 7 Comparisons of simulation results for evolution history of the Kakkonda geothermal system, bmed on the one-dimensional transient thermal conduction models. Temporal changes of the temperatures,at six depths (1.5 to ***4.0*** *km depth from the surface), calculated based on* ***K1****, K3,* ***KR1 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, andthe 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-1a well (Komatsu *etal.*, 1998). The KM2 model could improve the discrepancies between the simulated and reported maximum temperatures lor the contact metamorphism increasing with the depths (Fig. 5, bottom).

Some more simulation analysis wasconducted base 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 anddynamicenvironment 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 understandng the evolution history of the Kakkondageothermal system, where the actual times of the magma emplacement and the reservoir formation are not clear yet, the following two points obtained by extendng 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 temperatures only for a short period (*e.g.* for 50,000 to 100,000 years).

(2) The cooling rate of the conduction Qminated 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 dstributions (*e.g.* Takeno et *al.* (1999))) were obtained.

(2) Applicability of the above one-dmensional 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 *d.* (1998)), though large uncertainties remain. The latest microearthquake studies (*e.g.* Tosha and Nishi (1999)) suggested that the dstribution 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 bcdy.

(3) Another important problem to be solved is formation mechanism of the present hydrothermal system (*e.g.* Muraoka *et al.* (1998), Doi *et d.* (1998), Shigeno (1999b)). The latest K-Ar dating study for alteration minerals (Akatsuka etal., 1999) indicated that hydrothermal activities occurred not only near present time, but also *ca.* 5 Ma, probably by the emplacement of the Torigoenotaki 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-dmensional transient thermal conduction models, in which high 'extended thermal conductivity' (*Kext*) 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 modfied 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 obsetved and

simulated temperature profiles for the contact metamorphism.

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