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Hydrothermal and Heat Source Model for the Kakkonda Geothermal Field, Japan

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ABSTRACT

This paper summarizes the deep-seated geothermal resource surveys in the Kakkonda field, from the viewpoint of geothermal modeling. The results of surveys by NEDO and reanalysis of data by GSJ were reviewed in terms of reservoir and thermal structure modeling based on the NEDO and GSJ reports of the project. These models were compared to each other and summarized. The temperature decline model of the Kakkonda deep geothermal system was proposed based on the comparison with the Fournier model (1999).

1. INTRODUCTION (INITIAL MODELING FOR DEEP-SEATED GEOTHERMAL SYSTEM)

The possibility of the existence of deep-seated geothermal resources (deeper than 2,000m below ground) was investigated for the first time by the national project “Survey of large-scale deep geothermal development with regard to environmental conservation” (1978-1985) at the Hohi area in Kyushu, Japan, and high temperature steam was confirmed from a depth deeper than 2500 m (MITI, 1987). It was proved that deep-seated resources occur along vertical fracture zones where the upper surface depth of pre-Tertiary basement changes rapidly. Following that, another national project “Confirmation study of the effectiveness of exploration techniques for deep geothermal resources” at the Sengan and the Kurikoma areas from 1980 to 1988, proved that deep-seated geothermal resources occur not only along deep fracture zones but also on and around the Neogene granitic rock mass intruded into pre-Tertiary basement. The deep-seated reservoir discovered in the Sumikawa field in the Sengan area proved that the resource is higher in temperature and at a larger scale compared to shallow reservoirs. Following the result of these projects, a new national project “Deep-seated geothermal resources survey” was designed and carried out in the Kakkonda field from 1992 to 2000. The purpose of the project was to complete a 4 km deep drill hole and to clarify the existing conditions of the heat sources, to understand the overall geothermal environment including the shallow system and to evaluate the possibility of utilizing deep hydrothermal fluids. The initial conceptual model at the start of the investigation is shown in Fig. 1 (Kato et al., 1993).

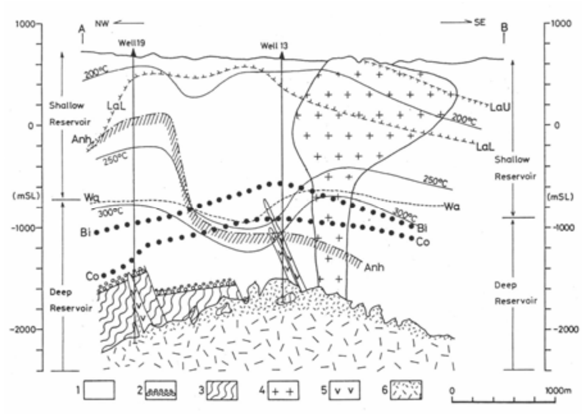

Figure 1: Schematic geologic cross section of the Kakkonda geothermal field (Kato et al., 1993)

1: Tertiary formation, 2. Basal conglomerate in Tertiary formation, 3. Pre-Tertiary formation, 4. Torigoenotaki Dacite Intrusion, 5. Old tonalite intrusion, 6: Neo-tonalite or quartz diorite pluton. The pluton is composed of medium-grained rock facies and partly pegmatic at the margin. LaU: Upper limit of laumontite, LaL: Lower limit of laumontite, Anh: Upper limit of anhydrite, Wa: Lower limit of wairakite, Bi: Biotite isograd, Co: Cordierite isograd.

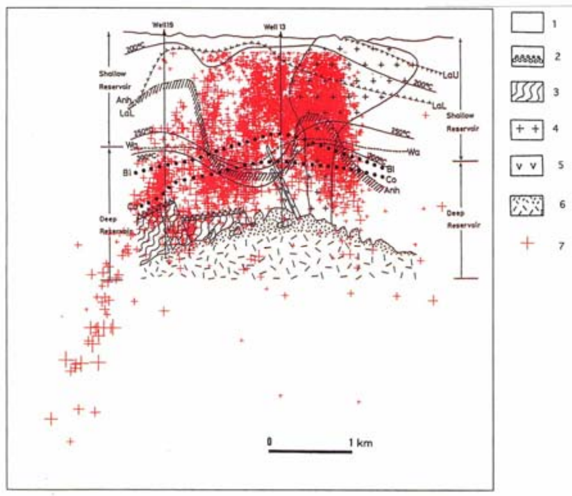

Figure 2: Distribution map of micro-earthquake hypocenter in the Kakkonda geothermal field (Sugihara, 1994). Micro-earthquake hypocenters are shown with red cross mark (legend 7) on the geologic cross section drawn by Kato et al.(1993). Other legends are same as Figure 1.

2. VARIOUS MODELS IN TERMS OF RESERVOIR AND HEAT STRUCTURES

To generalize the deep-seated geothermal models, many models presented by NEDO (New Energy and Industrial Technology Development Organization) and GSJ (Geological Survey of Japan) were considered from a viewpoint of permeability structure and heat structure. The map showing the distribution of the micro-earthquake hypocenters was very important at the start of the project because it suggested the locations of reservoirs and ascending paths of geothermal fluids as shown in Fig. 2 (Sugihara, 1994).

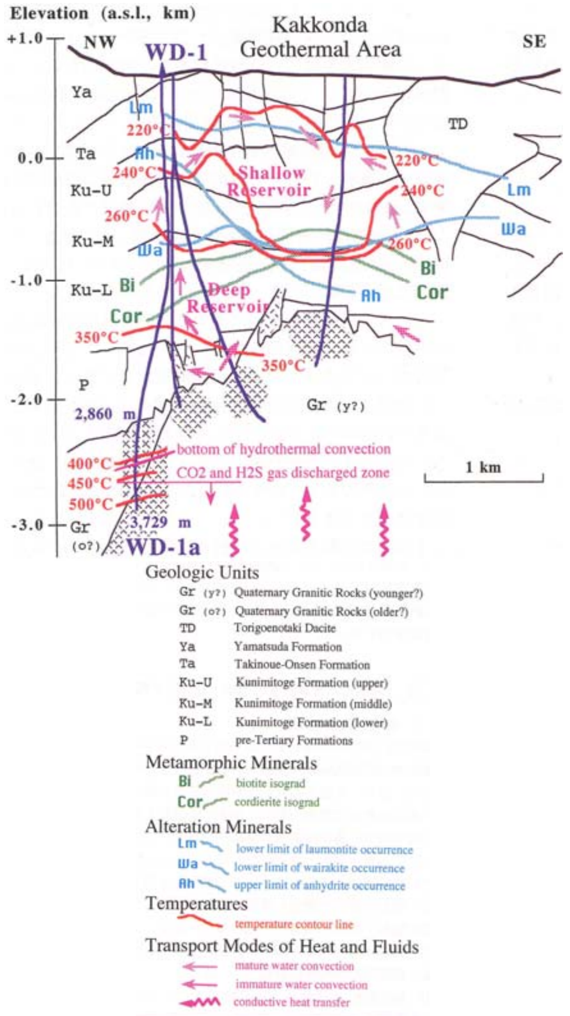

Figure 3: Cross section and model of magma (igneous)-hydrothermal system at the Kakkonda geothermal area (Uchida et al., 1996, Shigeno, 2000)

2.1 Reservoir structure model

<u>2.1.1 Geology, hydrothermal alteration and thermal metamorphism</u>

The occurrence of geothermal reservoirs is recognized at places where there is high temperature, and water circulation. High temperatures are provided regionally from magma residual heat. The potential heat sources for present active geothermal system are regarded as magma chambers younger than 0.6 Ma (e.g. Tamanyu, 1991). In the case of the Kakkonda field in Sengan area, the heat source is regarded as hot dry rock of Kakkonda granite, and the places where the water circulates are where permeable open fractures exist. These highly permeable fracture zones are generally identified in Tertiary/pre-Tertiary formations at wing parts of folding, and also in the periphery of intrusive bodies (NEDO, 1999). The permeability coefficient of the Kakkonda granite was measured as higher than 100μD (10^{-16} m^2) which is a high value compared to that of common granites. These porous features are interpreted as having been formed at a stage just after magma solidification and its following alteration (Fujimoto, et al., 1998). However, the permeability coefficient of the Kakkonda granite is smaller than that of the lower reservoir in the lower Tertiary (> $5x10^{15}$ m^2), therefore, the deep drill hole, WD-1a could not encounter the reservoir in the Kakkonda granite. The distribution depths of metamorphosed minerals record the highest temperature in the past (Fig. 3).

On the other hand, the distribution depth of anhydrite records the temperature condition of the shallow reservoir which has been influenced by the present deep geothermal system. The upper and/or bottom limits of occurrences of thermal metamorphosed minerals in aureole are interpreted to record the isograds of paleo-temperature. Based on the isograds of biotite and cordierite, estimated temperatures at formation of aureole were 200□ higher than the present isotherm (Fig. 4). The application of contact aureole analysis, melt inclusion analysis and pyroxene geothermometer revealed the history of hydrothermal activities as follows. The contact aureole was formed at the time of intrusion of Kakkonda granite, then meteoric water infiltrated into the deeper part, and resulted in the formation of the active hydrothermal system (Fig. 5).

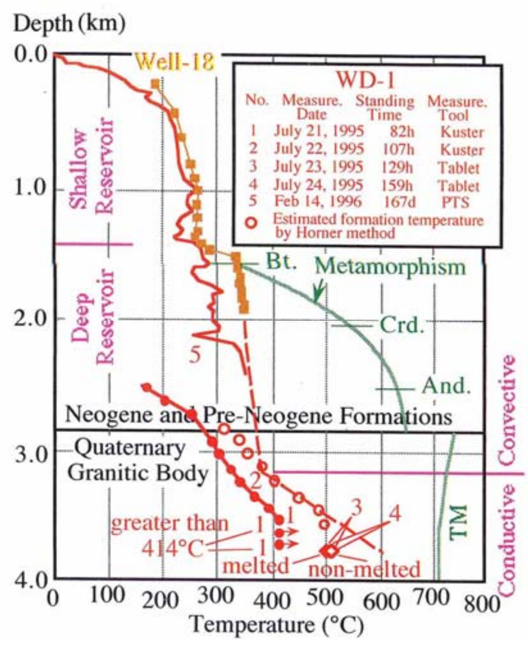

Figure 4: Temperature profiles of present logging and past contact metamorphism for the deep exploration well, WD-1a, at the Kakkonda geothermal area (Sasaki, et al., 1998, Shigeno, 2000). Bt., Crd. And. are isograds for biotite, cordierite and andalusite, respectively, and TM is ternary minimum curve of granitic melt.

<u>2.1.2 Fracture system and stress fields</u>

Under the present regional stress field, the fractures close to critical region of failure on the Mohr circle are regarded as more hydraulically conductive by Barton et al., (1997). However, a comparison between theoretical estimation by their methods and real conductive fractures does not agree. This disagreement suggests that tensile fractures produced by increase of pore pressure should be taken into consideration for their contribution to the conductivity. It should be also taken account that the brittle-plastic boundary migrated downward and the stress fields near boreholes are frequently different from the regional stress field (NEDO, 1999).

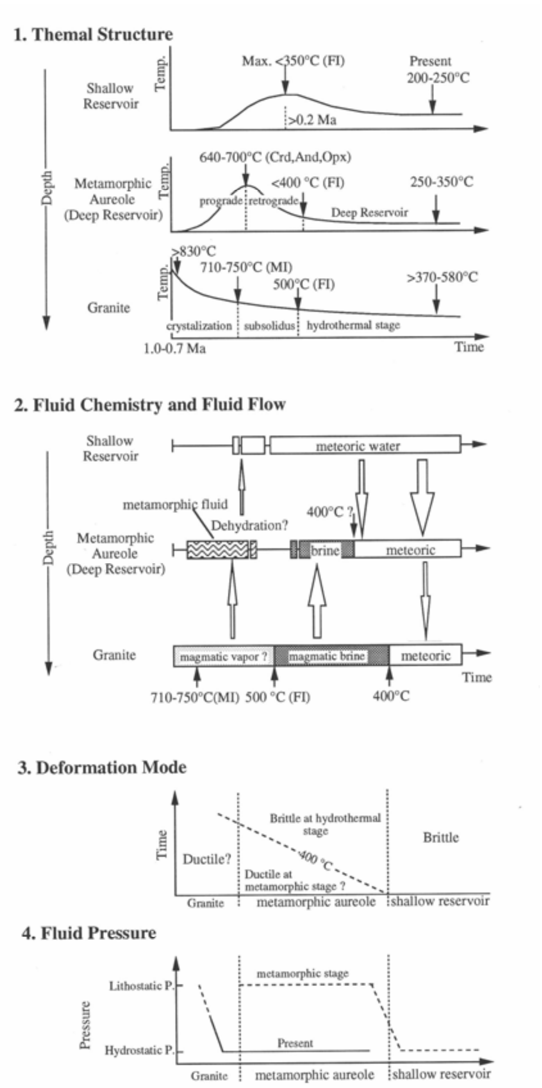

Figure 5: Temporal changes of fluids chemistry, deformation mode and fluids pressure after emplacement of Kakkonda granite (unpublished diagram drawn by Sasaki), FI: Fluid inclusion, MI: Melt inclusion

2.1.3 Reservoir model

The shallow reservoir has a relatively high permeability compared to the deep reservoir where most of the fractures are sealed by hydrothermal minerals, except for some hydraulically conductive fractures. The reservoir in the Kakkonda granite seems to be rare in occurrence because cooling joints and share fractures in the granite have insufficient space to trap the geothermal fluids (NEDO, 1999). The deep reservoir is still expected to occur not within but surrounding the Kakkonda granite, therefore those surrounding areas are regarded as future exploration target areas.

2.2 Thermal structure model

The alternative geothermal heat source, the so-called Neo-granite type was proposed besides the youngest volcanism related magma chamber as shown in Fig. 6 (Tamanyu, 1991, partly revised, 2000, 2001). This is a cross-section nearly east - west through Mt. Iwate, Kakkonda and Nyuto fields in the southern part of Sengan. This model indicates that neo-granite intrusion occurs behind the young volcanic front, and neo-granite intrusions provide more potential geothermal fields in comparison to the young volcanoes. Neo-granite is categorized as Quaternary granite. The neo-granite could be classified into the smaller cupola-shaped intrusion separated from the big underlying pluton, and the big pluton itself. The neo-granite named the Kakkonda granite is a stock several tens of square kilometers in area with an upper contact about 1.5-3 km deep, and is a composite pluton varying from tonalite to granite (Doi et al., 1998).

The subsurface temperature distribution maps at four levels (0, -500, -1000, -2000 m asl) were developed for the Sengan geothermal area including the Kakkonda field on the basis of borehole temperature logging data (Tamanyu et al., 1996). The temperature distribution map at -2,000 m indicates that the high temperature zone forms the shape of an eastwardly convex horseshoe, and it is generally consistent with the distribution of Quaternary volcanics. This high temperature zone suggests the concealed big pluton (Tamanyu, 2000, 2001) (Fig. 7). The total area over 250°C at -2 km asl reaches 390 km^2, and is almost equivalent to the areas of The Geysers in USA, Larderello in Italy and greater Tongonan in Philippine at the same condition (Tamanyu, 1995). The numerical simulation for reconstruction of the natural state of geothermal reservoir, proposed the inflow model of 39 MWt from the deep conductive zone to the deep and shallow reservoirs. The amount of inflowing heat is moderate compared to the whole production amount of 80 MWe equivalent to total electric generation (NEDO, 1999). The depth of 3,100 m at WD-1a is regarded as the transitional zone between hydrothermal convection and heat conduction based on the temperature profile pattern (Fig. 4). The horizon of this depth is equivalent to the subsurface isotherm of 380°C. This temperature is generally correlative to the transition of brittle–plastic deformation because the cut-off plane of microseismic hypocenters is almost concordant to the 380°C isotherm.

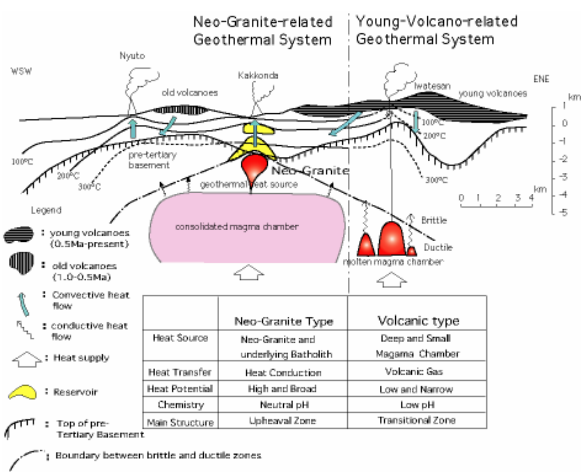

Figure 6: Geothermal heat source model for Kakkonda and its surrounding area (Tamanyu, 1991, partly revised, Tamanyu, 2000, 2001).

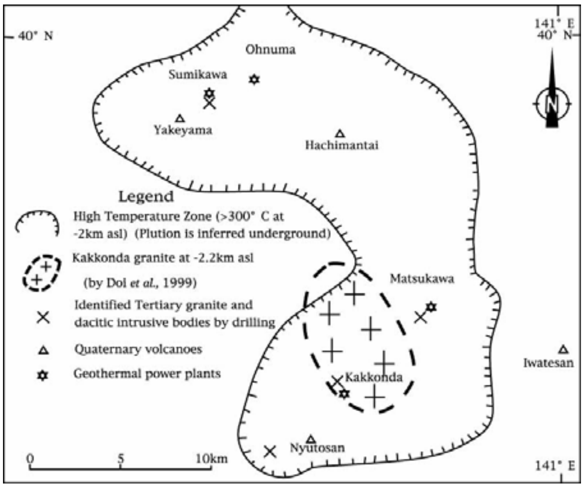

Figure 7: Distribution map of large Quaternary pluton estimated from high temperature zone (Tamanyu, 2000, 2001).

3. CONCLUSION (TEMPERATURE DECLINE MODEL)

Fournier (1999) proposed a schematic model of the transition from magmatic to epithermal conditions in a subvolcanic environment at the top of intruded plutons (Figure 8). The following descriptions are from Fournier (1999). In the brittle region, the stress difference required to cause shear failure of a preexisting open crack increases with increasing depth and is relatively independent of temperature, rock type, and strain rate. It is, however, highly dependent on the coefficient of friction, on pore fluid pressure, and on the orientation of the fracture with respect to the stress field. In contrast to the conditions for brittle failure, the stress difference required to initiate plastic deformation is highly dependent on temperature, strain rate, and rock type (material constants), and it is little affected by confining pressure. To date, the few deep wells drilled to temperatures greater than 370°C either have encountered little permeability or have produced gas-rich brines at greater than hydrostatic pressure (Fournier, 1991). These observations indicate that the brittle-plastic transition commonly occurs at about 370°C to 400°C within presently active continental hydrothermal systems. The well data also show that a narrow zone or shell of relatively impermeable material commonly separates the hydrostatically pressured domain from a domain in which fluid at greater than hydrostatic pressure may accumulate in apparently quasiplastic rock. A narrow, self-sealed zone of relatively impermeable material separates the lithostatically pressured region from a region where meteoric-derived hydrothermal fluids circulate through brittle rock at hydrostatic pressure. Episodically, major breaches of the self-sealed zone occur, and several different mechanisms temporarily increases the local strain rate to such a degree that previously plastic material undergoes shear failure in response to a very small stress difference. This allows hypersaline brine and gas to be expelled quickly from the normally plastic region into the brittle, lower pressure and lower temperature domain, where epithermal veins are deposited as a result of decompression and cooling of the magmatic fluid. The resulting increase in fluid pressure and temperature within the brittle domain leads to faulting and brecciation that increase permeability and allow an increase in the rate of discharge of hydrothermal fluid.

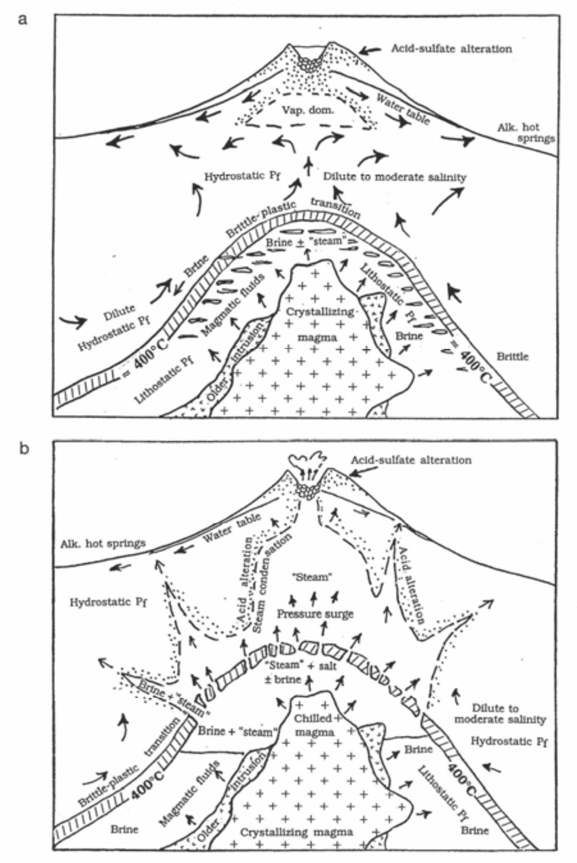

Figure 8: Schematic model of the transition from magmatic to epithermal conditions in a subvolcanic environment at the top of the intruded plutons (Fournier, 1999).

(a) The brittle to plastic transition occurs about 370°C to 400°C and dilute, dominantly meteoric water circulates at hydrostatic pressure in brittle rock while highly saline, dominantly magmatic fluid at lithostatic pressure accumulates in plastic rock. (b) Episodic and temporary breaching of a normally self-sealed zone allows magmatic fluid to escape into the overlying hydrothermal system.

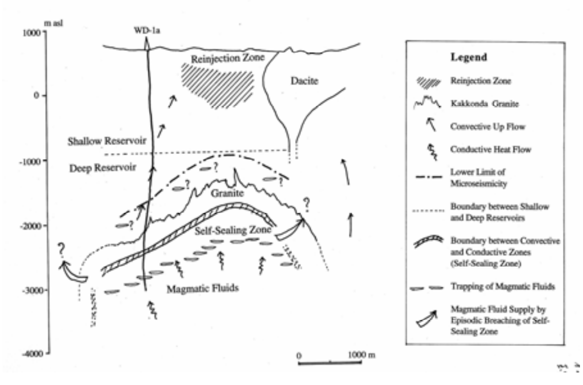

Figure 9: Temperature decline model for the Kakkonda geothermal model (Tamanyu and Fujimoto, 2000).

In the intermediate summary of the project "Deep-seated geothermal resources survey" Uchida et al. (1996) presented a model of the magma (igneous) – hydrothermal system at the Kakkonda geothermal area (Fig. 3). Other detailed models of the thermal and hydraulic structure were also presented by NEDO (1999). The authors compared these specific Kakkonda models and the generalized model by Fournier (1999), then finally proposed the temperature decline model for the Kakkonda geothermal system (Fig. 9). In the conceptual model of Fournier (1999), a volcanic edifice is built on the surface, and the brittle-plastic boundary is in agreement with the boundary of a hydrothermal convection region and a heat conduction region, and also equivalent to the temperature zone of 370 to 400 °C. However, in the specific models of Uchida et al. (1996) and NEDO (1999), there is no volcano on the surface, and the brittle-plastic boundary is equivalent to the temperature zone of 300 to 320°C based on the lower cut-off plane of microseismicity (Tosha et al., 1998). The boundary between the hydrothermal convection region and the heat conduction region is regarded as 380°C, based on the knee point of thermal gradients in the temperature/depth curve -- which is the same temperature as the Fournier model. This indicates that Kakkonda has been cooled down quickly by surface and reinjected water, and followed by a downward migration of the transition between hydrothermal convection and heat conduction, although the cut-off plane of microseismicity did not change very much. In other words, the lower reservoir of the Kakkonda field is in a transforming process from a conductive regime to a hydrothermal convection regime without remarkable change of deformation behavior from plastic to brittle. These complicated changes have not yet been reconstructed in numerical simulations such as the simplified-model simulation by Shigeno (2000).

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