

REVIEW OF RECENT DEVELOPMENT OF THE KAKKONDA DEEP RESERVOIR, JAPAN

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Abstract

There are two reservoirs with different temperature and permeability in the Kakkonda hydrothermal system. The shallow reservoir is permeable and 230 to 260°C, while the deep reservoir is less permeable and 350 to 360°C. However, they are hydraulically connected each other. Recent drilling of deep wells revealed existence of Pre-Tertiary formation below Tertiary formations and neo-granitic pluton younger than 5Ma. This pluton is a heat source of metamorphism found in Pre-Tertiary and Tertiary formations. There is a permeable horizon at the top of the pluton, and is very productive. To date, 4 production wells have been completed in this deep reservoir.

INTRODUCTION

The Kakkonda (Takinoue) geothermal field is located about 600km northeast of Tokyo (Fig.1) and is one of the most active liquid-dominated geothermal fields in Japan. The first power plant, Kakkonda Unit1, 50MWe, has been in operation since 1978 by Tohoku Electric Power Inc. (TEP), where Japan Metals and Chemicals Co., Ltd. (JMC) is a steam supplier. Currently, development for the Kakkonda Unit2, 30MWe, is being continued by Tohoku Geothermal Energy Co., Ltd. (TGE), a joint venture led by JMC. Its power generation is expected to start in 1996 by TEP. In the course of this development,

JMC Geothermal Research and Development Co., Ltd. (JMCD), a geothermal development operator fully owned by JMC, has been in charge of exploration, drilling, reservoir engineering studies and fundamental studies.

Before the start of the development for the Kakkonda Unit2, the reservoir shallower than 1,500m has been developed. However, due to the limited horizontal extent of the reservoir, it has become necessary to develop a deeper reservoir than 1,500m for both Unit1 and Unit2. Thus, a deep exploration well KT-208 (T.D. 2,126m) was drilled in 1985 and revealed geological and thermal characteristics of the deep reservoir. Then, the production well K6-2 (T.D. 2,818m) was drilled in 1989 and confirmed that the Kakkonda deep reservoir was very productive. Geological information from these deep wells revealed existence of Pre-Tertiary formation below Tertiary formations, neo-granitic pluton, and thermal metamorphic rocks created by the neo-granitic pluton.

These results encouraged the development of the Kakkonda deep reservoir. To date, 4 deep production wells (1 for Unit1 and 3 for Unit2) were completed without any trouble. In this report, we summarize outline of the development, hydrothermal characteristics and conceptual model of the Kakkonda deep reservoir.

OUTLINE OF THE DEVELOPMENT

Geothermal exploration in the Kakkonda area was started in 1958 by JMC in cooperation with Geological Survey of Japan. Exploration and development for the Kakkonda Unit1 was described by Nakamura and Sumi (1981) and Sato (1982). Its power generation was started in 1978 at the output of 50MWe, but it gradually decreased due to unexpectedly fast return of reinjected fluid (Nakamura, 1981; Horne, 1982). However, it was not necessarily avoidable, because of the lack of understanding of detailed three-dimensional permeability distribution and the lack of sufficient drilling pads especially for reinjection. Since Kakkonda is at the bottom of a steep valley and included in a national park, the geothermal development was restricted by the difficulty of finding flat land for drilling pads and getting permission for its use. Subsequently, the output was recovered to 45MWe in average, by offsetting reinjection wells to southeast and production wells to northwest. To relocate these wells, we employed a number of tracer tests and a three-dimensional history matching study with a double-porosity reservoir model (Nakamura, 1986).

Depth of production wells for the Kakkonda Unit1 ranged from 1,000m to 1,500m before the start of the development for the Kakkonda Unit2. However, we had been looking for possibilities of development of a reservoir of different depth. Thus, based on the following facts confirmed by existing wells, we thought development of the deep hot reservoir was feasible;

1) In-flow of very hot fluid of more than 300°C at the

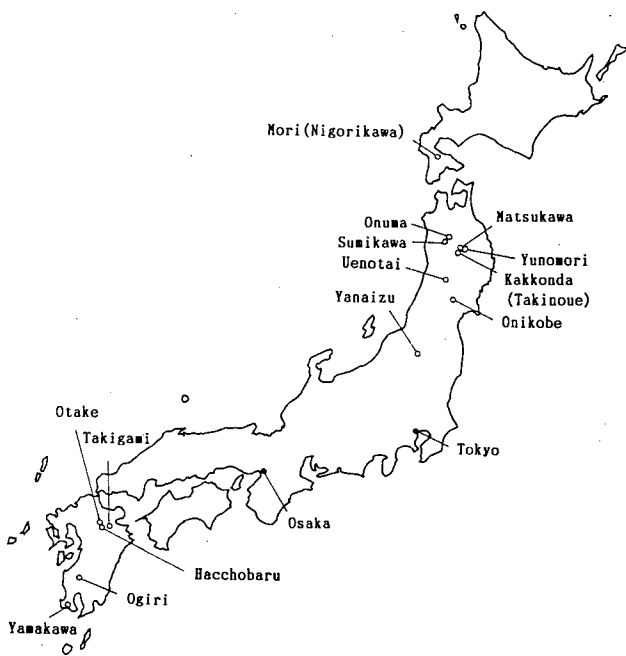


Fig.1 Location of the Kakkonda geothermal field

bottom of some wells of 1,500m depth, was confirmed though its rate was very small.

2) Some wells showed abrupt increase in bore hole temperature at around the bottom (Fig.2). This suggested that there was a very slow hydrothermal convection in great depth though its permeability was very low.

3) Micro-earthquakes existed below -2km sea level suggesting existence of fractures at such depth.

4) Distribution of the thermal metamorphic minerals suggested that its heat source such as neo-granitic pluton was not very far from the developed zone.

5) Results of interpretation of chemical data and the three dimensional history matching study suggested that there should have been small amount of in-flow of hot fluid into the shallow reservoir from the deep reservoir.

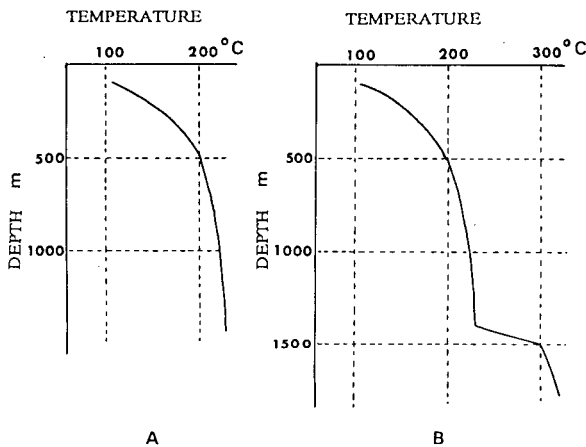


Fig.2 Schematic temperature profiles of the shallow wells (after Kasai et al., 1990). A: Ordinary shallow reservoir wells. B: Wells touched top of the deep reservoir.

The exploration well KT-208 was drilled during 1985 and 1986. From the results of this well (Fig.3), the deep reservoir of totally different hydrothermal characteristics, i.e. temperature and permeability, was confirmed to exist below approximately 1,500m (e.g. Doi et al., 1988). Production test of this KT-208 was tried in 1989. It was successful and confirmed that the deep reservoir was productive enough for commercial geothermal development, because of high pressure and high enthalpy, though its permeability was very low.

To develop this deep reservoir for the Kakkonda Unit2, the first deep production well K6-2, which targeted this deep reservoir, was drilled in 1989. Drilling of this K6-2 was described by Saito (1991; 1992). K6-2 first targeted 3,000m depth, but it encountered fractured zone at around 2,800m. It produces 63t/h of steam and 57t/h of hot water. This drilling revealed existence of Pre-Tertiary formation from 2,167m depth, neo-granitic pluton from 2,778m depth, and productive fractures of more than 300°C in the Pre-Tertiary formation and upper boundary of the neo-granitic pluton (Fig.4).

In 1990, K1-3 (T.D. 2,465m), the second deep production well for the Unit2, was successfully drilled. It encountered neo-granitic pluton exactly at the expected depth (2,344.5 to 2,463.4m) and confirmed horizontal extent of the deep reservoir. K1-3 produces 92t/h of steam and very small amount of hot water.

In 1992, K6-3 (T.D. 3,000m), the third deep production well for the Unit2, was also successfully

drilled. It encountered neo-granitic pluton at 2,832m exactly as expected. We tentatively confirmed by early production test, that K6-3 produced more than 100t/h of steam and almost the same amount of hot water.

GEOLOGICAL OUTLINE OF THE KAKKONDA DEEP RESERVOIR

Geology of the Kakkonda shallow reservoir has been described by Sato (1982) and Doi et al. (1988). Based on Doi et al. (1991) and Kato et al. (1993), we summarize geological characteristics of the Kakkonda deep reservoir. Schematic geologic sequence at the Kakkonda geothermal field is shown in Fig.5.

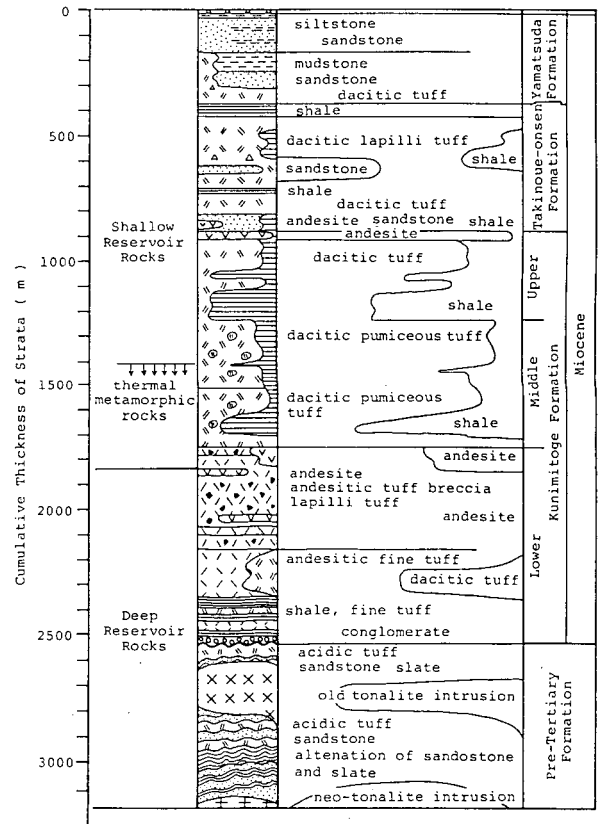


Fig.5 Schematic geologic sequence at the Kakkonda (after Kato et al., 1993).

Based on core samples taken at K6-2, the neo-granitic pluton is not metamorphosed and its alteration is very weak. It has texture of the shallow intrusion and consists of quartz, plagioclase, potassium feldspar, biotite, hornblende, cummingtonite, clinopyroxene and orthopyroxene.

Metamorphic minerals were found in depths deeper than 1,006m. They are in Pre-Tertiary formation, Tertiary formation (Kunitoge-formation) and intrusive rocks. They consists of green and brown biotite, muscovite, cordierite, anthophyllite, andalusite, hastingsite, cummingtonite, tremolite, pyrrhotite and magnetite. This metamorphism is more notable at depth, and texture of its original rock is sometimes lost at depths deeper than 2,500m. The horizontal area of this metamorphism ranges 2.0 x 2.5km. Accounting for the extent of this metamorphism and the neo-granitic pluton,

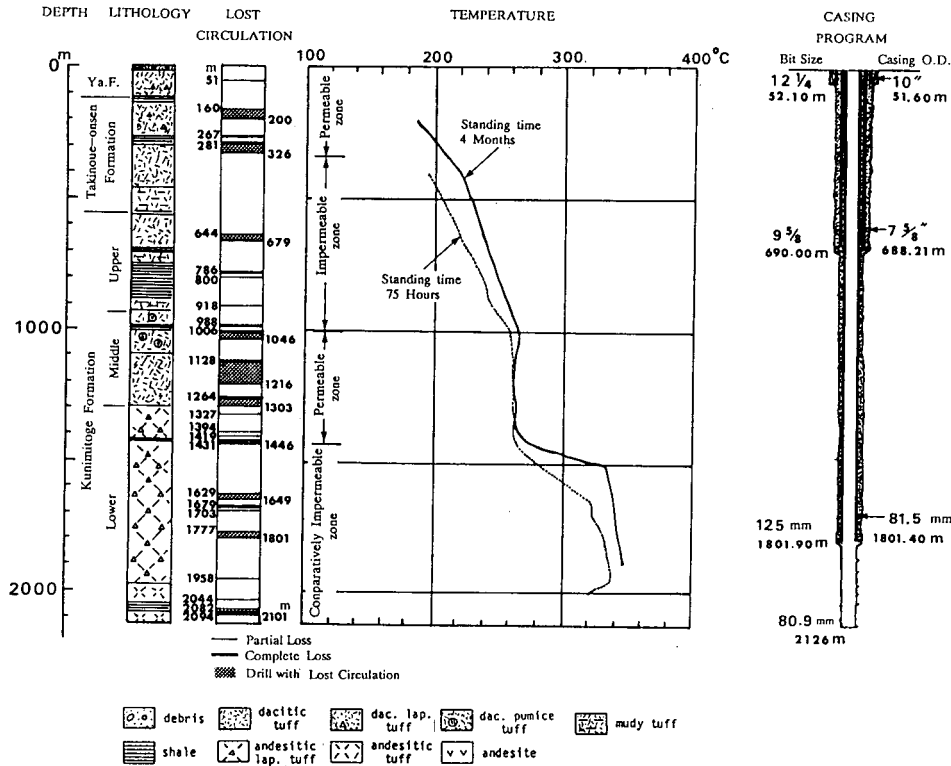


Fig.3 Geologic column and logging data of KT-208 (modified from Doi et al., 1988).

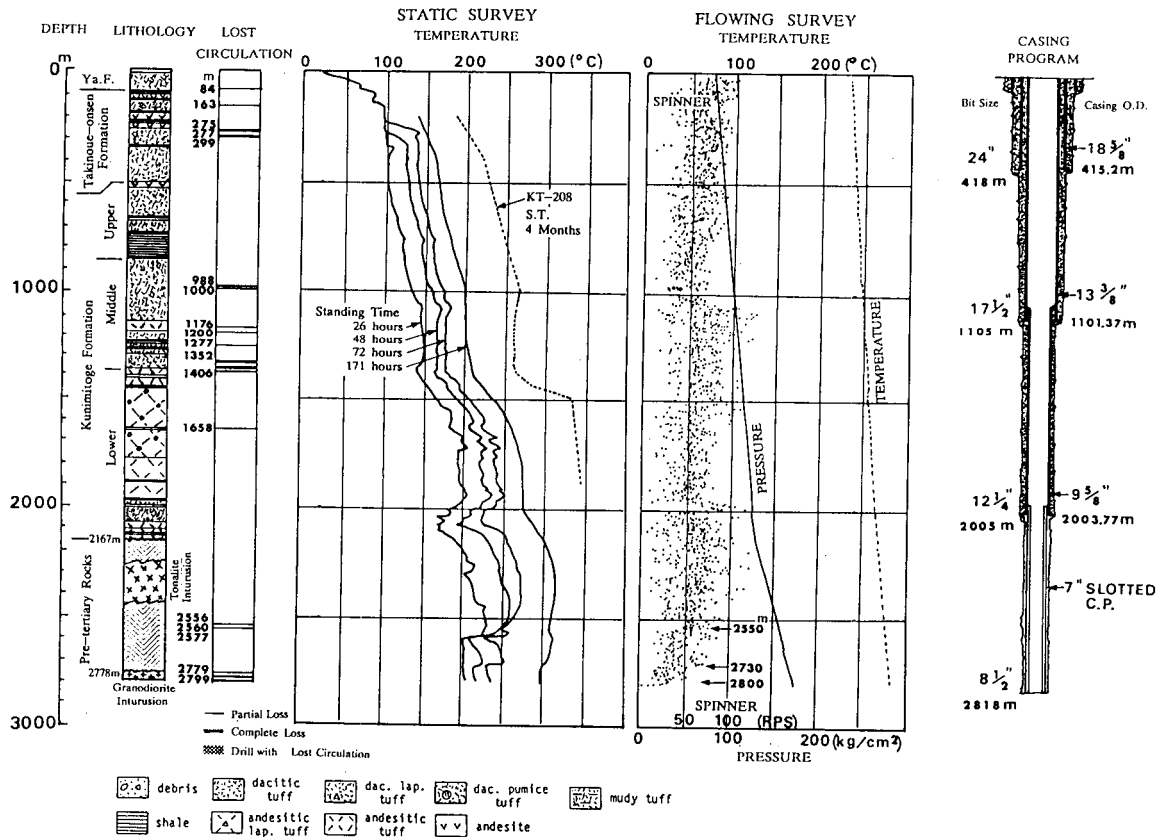


Fig.4 Geologic column and logging data of K6-2

and characteristics of the neo-granitic pluton as described above, it is clear that heat source of this metamorphism is the neo-granitic pluton. On the other hand, the latest rock which was metamorphosed is a dacite dike of 5Ma (Tamanyu, 1980). Thus, the neo-granitic pluton is younger than 5Ma.

The biotite was found at 19 wells and the cordierite was found at 10 wells. Vertical distance between the biotite and the neo-granitic pluton is approximately 1,000m and that between the cordierite and the pluton is approximately 700m (Fig.6). The depths of their appearance are shallower in northeast and slightly deeper in southwest. Thus, isograds of the biotite and the cordierite are good indicators of top of the neo-granitic pluton. Targets of K1-3 and K6-3 were decided based on these isograds.

The top of the neo-granitic pluton is also estimated from micro-earthquake data. The bottom of micro-earthquake distribution in Kakkonda was found to be very close to the confirmed top of the pluton (Fig.7). That is, micro-earthquakes occur in permeable zone of Tertiary and Pre-Tertiary formations but they do not occur within the neo-granitic pluton. Based on trend of the biotite and cordierite isograds, distribution pattern of deep micro-earthquakes in northwest and southeast (Fig.7) probably indicate shape of outline of the neo-granitic pluton.

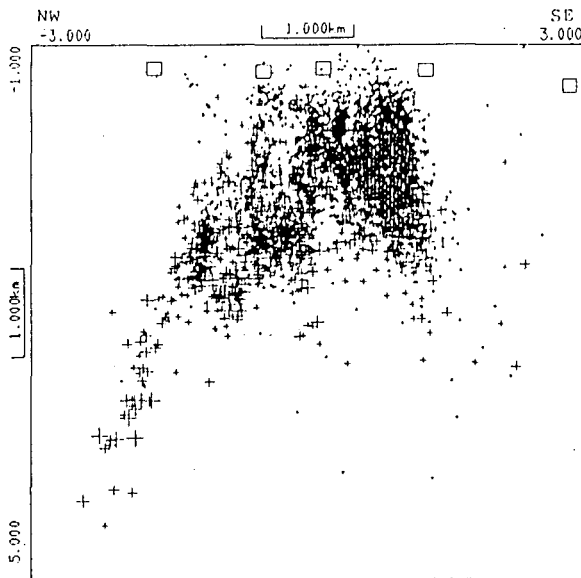


Fig.7 Northwest-southeast cross section of the micro-earthquake hypocenter distribution at Kakkonda (after Sugihara, 1991). Open squares are some of the micro-earthquake observatories.

THE KAKKONDA HYDROTHERMAL SYSTEM

Before the start of the development of the deep reservoir, the model of the Kakkonda hydrothermal system used be as follows (e.g. Sato, 1982). That is, the Kakkonda geothermal reservoir is a combination of horizontal fractures which develop at the bottom of a syncline, and vertical fractures such as faults and shear zones. Temperature profiles of wells in syncline zones are convective, while some of the southeastern wells in lower reach of the Kakkonda river show conductive profiles. Thus, there is a permeable zone with lots of fractures and hydrothermal convection in it, while there is a less

permeable zone which dominates in heat conduction surrounding the permeable zone. In this permeable convection zone, high enthalpy fluid which entered from the deep zone heats meteoric-origin fluid and forms the Kakkonda shallow geothermal reservoir.

Later, static temperature of the deep wells, such as KT-208 and K6-2, were found to show abrupt increase at around 1,500m depth (Figs 3 and 4). This indicated existence of two different convection cells, thus the Kakkonda hydrothermal system was found to consist of two reservoirs with different characteristics; the shallow reservoir (shallower than approximately 1,500m) and the deep reservoir. The shallow reservoir is very permeable and 230 to 260°C, while the deep reservoir is less permeable and 350 to 360°C. Fluid flashes in the wellbore at almost all the shallow wells, but because of high enthalpy it flashes in the reservoir at the deep wells.

Reservoir pressures of these deep wells are on a line of current reservoir pressures of the shallow reservoir (Fig.8). Thus, this deep reservoir is hydraulically connected to the shallow reservoir, and responding to the exploitation of the Unit1.

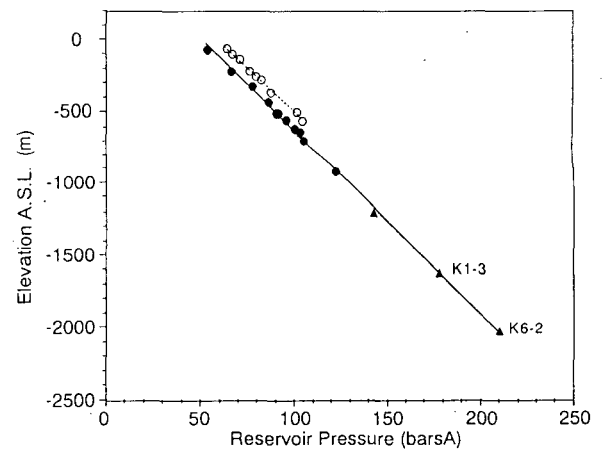


Fig.8 Reservoir pressure profile at Kakkonda. Solid circles: current data of the shallow reservoir. Solid triangles: current data of the deep reservoir. Open circles: initial data of the shallow reservoir.

Applying one-dimensional vertical advection model described by Turcotte and Schubert (1982, p.399), we analyzed temperature profiles of both shallow wells and deep wells. This result suggests that the average vertical permeability is around $10^{-14}m^2$ in the shallow reservoir but it is much lower in the deep reservoir, it is possibly around $10^{-16}m^2$. Based on the linear stability analysis (e.g. Turcotte and Schubert, 1982, p.404), this value ($10^{-16}m^2$) is very close to the minimum critical value for the onset of hydrothermal convection in the deep reservoir. Thus, the hydrothermal convection in the deep reservoir evolved upon very critical hydrothermal conditions.

However, as seen in Figs 3, 4 and 6, complete lost circulation always occurred when the wells encountered the permeable horizon in the deep reservoir, i.e. the top of the neo-granitic pluton. Thus, the permeable horizon in the deep reservoir is very permeable and its kh (permeability thickness product) was found to be order of $10^{-12}m^3$ by both single well tests and a pressure interference test. This relatively high permeability, high pressure and high enthalpy result in high productivity of

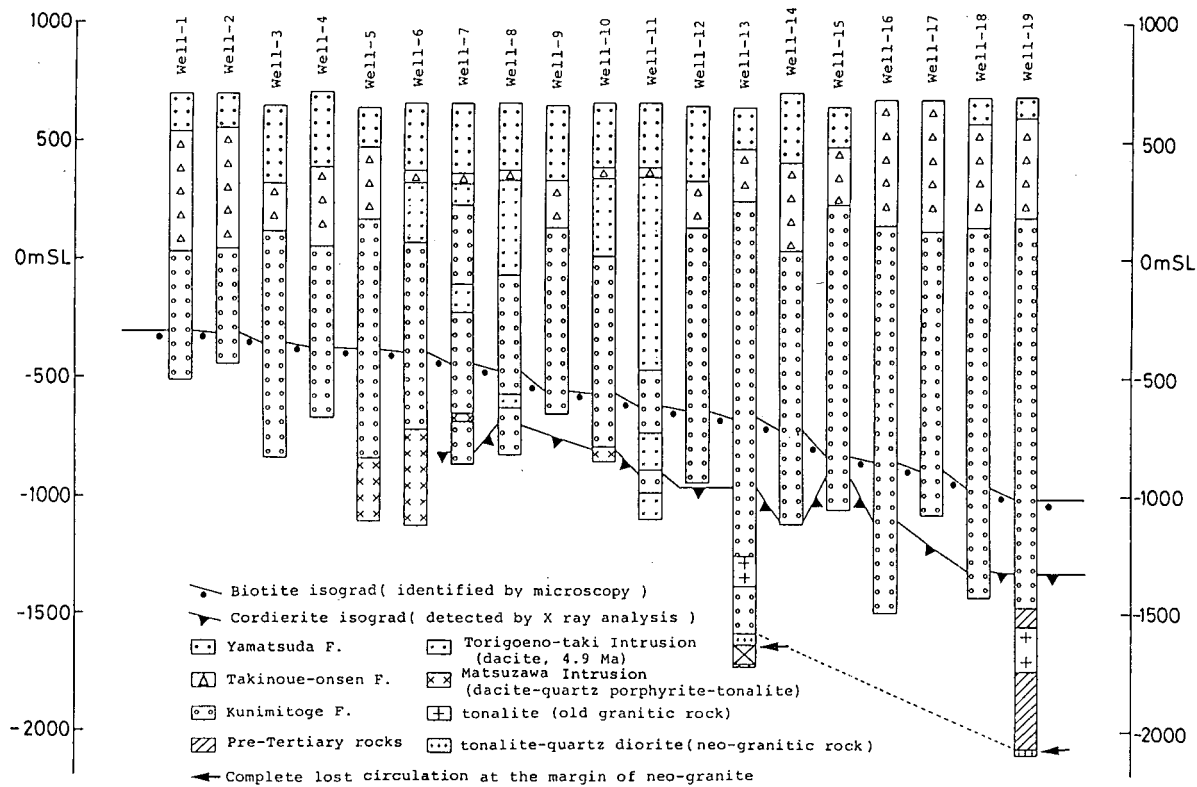


Fig.6 Distribution of metamorphic minerals in wells at Kakkonda (after Kato et al., 1993). Well-13 is K1-3, and Well-19 is K6-2.

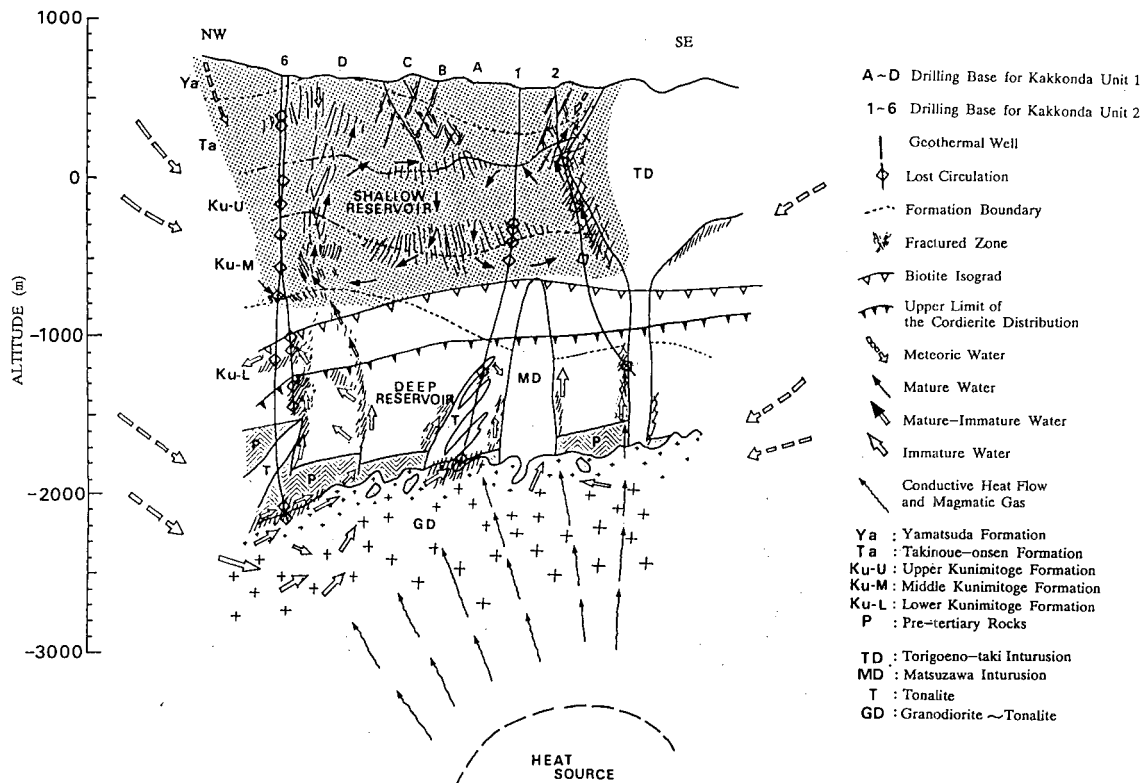


Fig.9 Conceptual model of the Kakkonda hydrothermal system.

the deep wells. The most important fractures for production in the deep reservoir are marginal ones at the top of the neo-granitic pluton and those associated with intrusion of the pluton in the Pre-Tertiary formation, but some minor fractures do exist in the Tertiary formations in the deep reservoir.

Fluid in the shallow reservoir, sampled by a Kuster tool in wells at depths deeper than flashing points, is slightly alkaline and pH is around 8 (e.g. Kasai et al., 1990). However, fluid from deep wells sampled at the well heads is rich in Cl and acid, with pH being 3.3 to 4.5. (Yanagiya, 1990). From an isotope study, this acid fluid was found to be a so-called "immature water", i.e. a mixture of meteoric water and, HCl and SO₂ contained in volcanic gas.

A conceptual model of the Kakkonda hydrothermal system based on above discussions is shown in Fig.9.

CONCLUDING REMARKS

The development of the Kakkonda deep reservoir has become promising by the success of the recent deep wells. The Kakkonda shallow reservoir has been characterized by production of large amount of hot water with steam. This raised a problem of large amount of reinjection and return of reinjected fluid into production wells. However, using deep wells which produce much less hot water than the shallow wells, we will be able to reduce amount of reinjection. This is favorable for our development. With less reinjection, we will be able to reduce rate of the temperature decrease in the shallow reservoir due to return of reinjected fluid, and will be able to continue constant power production not only at the Unit2 but also at the Unit1. Based on the distribution of the metamorphic minerals and micro-earthquakes, the neo-granitic pluton is large enough. Thus, we are planning to confirm its distribution and extent by further deep drilling.

Acknowledgments

Success of the development of the Kakkonda area is a result of efforts by a number of colleagues in Japan Metals and Chemicals Co., Ltd. (JMC), Tohoku Geothermal Energy Co., Ltd. (TGE) and its group. We would like to pay our respects to their continuing efforts. We are grateful to JMC and TGE for their permission to publish this paper. We also would like to thank Ko Sato of JMC for his review of this manuscript, and our colleagues in JMC Geothermal Research and Development Co., Ltd., especially Nobuo Doi and Yutaka Yoshida, for their discussions and suggestions.

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