HYDROTHERMAL CONVECTION SYSTEM OF THE KAKKONDA GEOTHERMAL FIELD, JAPAN

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Abstract

Hydrothermal convection in the Kakkonda liquid–dominated geothermal area evolved within a tectonically controlled fractured zone. There are two reservoirs with different temperatures 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 to each other. Recent drilling of deep wells revealed existence of neo–granitic pluton (Kakkonda Granite) with an age of 0.34 to 0.07Ma. This pluton is a heat source for metamorphism in the Kakkonda reservoir, however, accounting for the regional temperature distribution, this pluton is only one of the heat sources of this area. A micro–earthquake study revealed that the up flow into the reservoir came from great depths from the northwest of the 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 Unitl, 50MWe, has been in operation since 1978 by Tohoku Electric Power Inc. (TEP), and 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 will be started in 1996 by TEP. Locations of drilling pads in the Kakkonda area are shown in Fig.2. In the course of this development, JMC Geothermal Engineering Co., Ltd., a geothermal development operator owned by JMC, has been in charge of exploration, drilling, reservoir engineering studies and fundamental studies.

Fig.1 Location **of the Kakkonda geothermal field**

The Kakkonda hydrothermal system is an unconfined system and has a two distinct layered structure both in temperature and permeability. Before the start of the development for the Kakkonda Unit2, the reservoir shallower than 1,500m was 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 Unitl and 2. The shallow reservoir is very permeable at 230 to 260°C, while the deep reservoir is less permeable at 350 to 360°C. Exploration and development of the Kakkonda shallow and deep reservoirs are described by Nakamura and Sumi (1981) and Hanano and Takanohashi (1993) for example. Recently New Energy and Industrial Technology Development Organization (NEDO) has started a study on deep–seated geothermal resources in Kakkonda (e.g. Yagi et al., 1994). In this paper, the structure of the Kakkonda hydrothermal convection system is discussed based on temperature and other data.

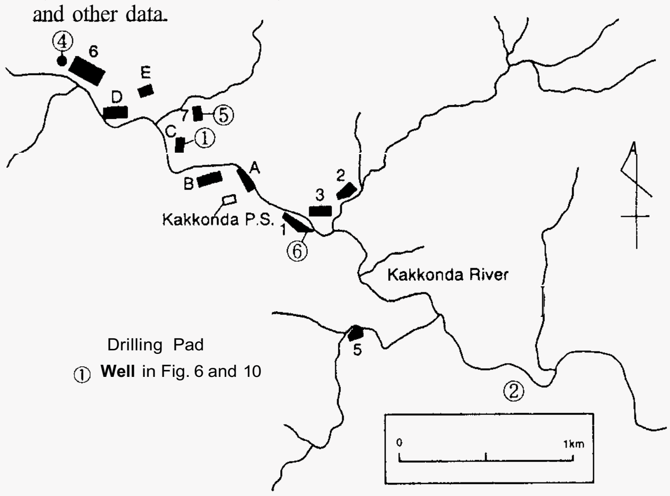

Fig.2 Location of drilling pads and wells

GEOLOGICAL OUTLINE

Geology of the Kakkonda reservoir has been described by Nakamura and Sumi (1981), Sato (1982), Doi et al. (1988), Kato et al. (1993), Kato and Doi (1993), Koshiya et al. (1993, 1994) and Komatsu and Muramatsu (1994) for example. We follow those reports to summarize geological characteristics of Kakkonda.

The geology of the Kakkonda geothermal field is composed of Tamagawa Welded Tuffs, Miocene formations, Pre–Tertiary formations, old intrusive rocks and the neo–granitic pluton (the Kakkonda Granite). The Miocene is divided into Yamatsuda F., Takinoue–onsen F., and Kunimitoge F., in descending order. In Kakkonda, very highly fractured Miocene formations outcrop along the Kakkonda river, therefore there are a lot of surface geothermal activities, such as hot springs and fumaroles. Distribution of such surface geothermal activities is shown in Nakamura and Sumi (1981). The Kakkonda geothermal reservoir consists of formations below the Yamatsuda F. Many old intrusive rocks, such as Torigoeno–taki dacite, Matsuzawa dacite and porphylite are distributed in this field, and intrude into the Miocene series. Torigoeno–taki dacite has K–Ar age of 4.9±1.0Ma (Tamanyu, 1980), and Tamagawa Welded Tuffs has an age ranging from about 2.0 to 1.0Ma (e.g. Suto, 1982). Koshiya et al. (1993) show that the paths of geothermal water are controlled by fractures with K–Ar age of K–feldspar of 0.2±0.1Ma.

Based on core samples, the Kakkonda Granite is not metamorphosed and its alteration is very weak. It has texture of a shallow intrusion. Metamorphic minerals were found at depths deeper than 1,006m in the Pre–Tertiary formation, Tertiary formation (Kunimitoge–

formation) and intrusive rocks. This metamorphism is more notable at depth, and the texture of its original rock is sometimes lost at depths deeper than 2,500m. The horizontal area of this metamorphism is 2.0 x 2.5km. Accounting for the extent of this metamorphism and the Kakkonda Granite, and the characteristics of the Kakkonda Granite described above, it is clear that the heat source of this metamorphism is the Kakkonda Granite.

Biotite and cordierite, some of the above mentioned metamorphic minerals, were found in 21 wells and 11 wells respectively. Vertical distance between the biotite and the Kakkonda Granite is approximately 1,000m and that between the cordierite and the pluton is approximately 700m. The depths of their appearance is shallower in the northeast and slightly deeper in the southwest. Thus, isograds of the biotite and the cordierite are good indicators for the top of the Kakkonda Granite. Minerals separated from the neo–granite have different K–Ar ages; those of the hornblende and the biotite are 0.34 to 0.08Ma and 0.21 to 0.07Ma respectively (Kanisawa et al., 1994). A schematic geologic cross section of the Kakkonda geothermal field is shown in Fig.3.

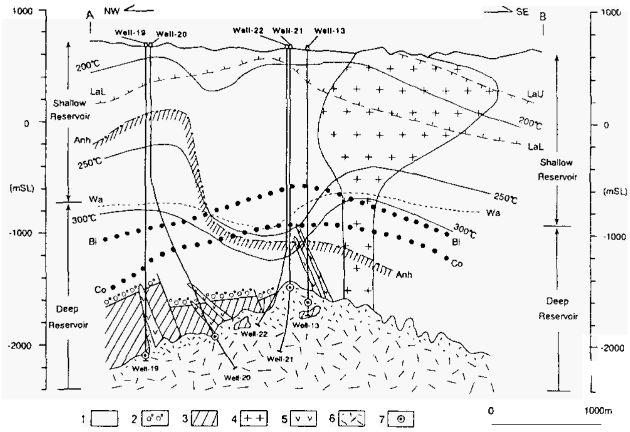

Fig.3 Schematic geologic cross section of the Kakkonda geothermal reservoir along the Kakkonda river (Kanisawa et al., 1994). 1: Tertiary formations, 2 Basal conglomerate in Tertiary formations, 3: Pre–Tertiary formations, 4: Torigoeno–taki dacite intrusion, 5: Old granitic intrusives, 6 Neo–granitic pluton (Kakkonda Granite), 7: Points of K–Ar dating. 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.

In Fig.3, the distribution of anhydrite is notable; it is distributed shallower in the northwestern part. The anhydrite precipitates at high temperature. Thus, this distribution suggests that hot up flow exists in the northwestern part of the reservoir; *i.e.* in the direction of upper reaches of the Kakkonda river.

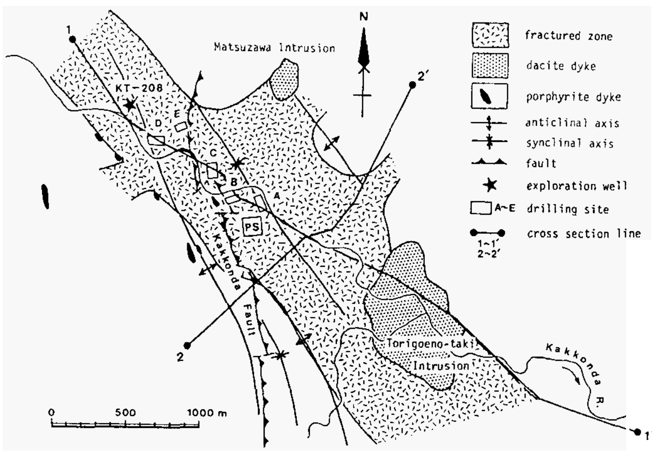

Fig.4 Distribution of fractured zone in the shallow reservoir (Doi et al., 1988).

Permeability in the Kakkonda reservoir originates from fractures as described above. Thus fluid production and reinjection are possible only when wells encounter large enough fractures which permit fluid flow into or out of the wells. However, horizontal extent of the fractured zone was found by drilling to be limited. Fig.4 shows this distribution of the fractured zone in the Kakkonda shallow reservoir. As seen in Fig.4, this fractured zone is generally distributed along the Kakkonda river which is one of the most distinct lineaments in this area. Thus, it is clear that occurrence and distribution of the fractures in the Kakkonda area are controlled by regional tectonic movement.

REGIONAL TEMPERATURE DISTRIBUTION

Regional temperature distribution at sea level, including the Kakkonda liquid–dominated geothermal field, the Matsukawa vapor–dominated geothennal field and Mt. Iwate, an active volcano, is shown in Fig.5. This elevation corresponds to approximately 600m depth at the center of the Kakkonda area. As seen in Fig.5, temperature distribution around the Kakkonda area gradually decreases towards the southeast. Static temperature profiles of wells in and around the Kakkonda geothermal field are shown in Fig.6. The well(1) in Fig.6 is a good production well drilled in the center of the Kakkonda shallow reservoir (Figs 2 and 5). Its temperature profile has a rapid increase in the very shallow part, and becomes constant at 230°C indicating the existence of a very active ascending flow of natural convection in this shallow reservoir. The 230°C is an average temperature in the lower reaches (southeastern part) of the Kakkonda shallow reservoir, while that of the upper reaches (northwestern part) is approximately 260°C. Such a temperature profile as well(1) is a representative of those of wells in the shallow reservoir. On the other hand, temperature of the deep reservoir suddenly increase at around 1,500m depth and reaches 350 to 360°C (Fig.13). The characteristics of the deep reservoir will be discussed later.

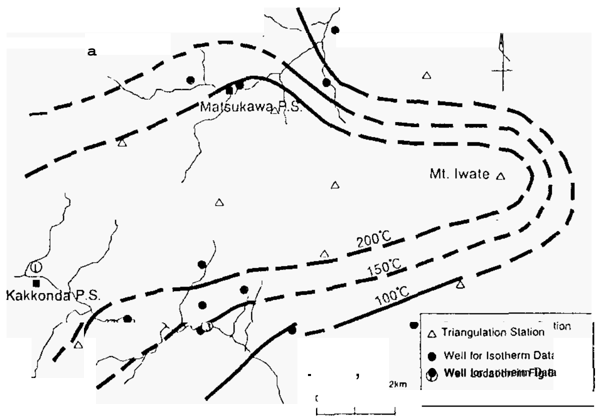

Fig.5 Regional temperature distribution at sea level (modified from Onuma, 1993).

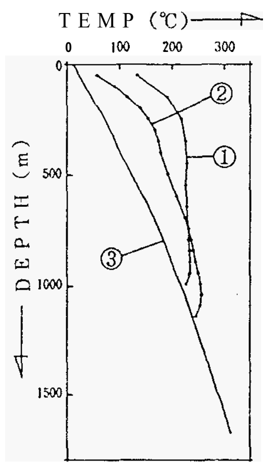

Fig.6 Static temperature profiles of wells in and around the Kakkonda area (Kajiwara et al., 1993). Well head elevations of wells (1), (2) and (3) are 676m, 586m and 488m above sea level, respectively.

Well(3) in Fig.6 is located about 5km away from the well(1). Since this well shows a conductive temperature profile, active hydrothermal convection does not exist in this area. Thus, there is no surface geothermal activity there. However, note that temperature of the well(3) exceeds 300°C below 1,600m depth.

Well(2) in Fig.6 is located in the middle between wells (1) and (3). Since this well has a convective but slightly conductive temperature profile, convective up flow is relatively weaker in this area than in the center of the Kakkonda reservoir. Wells in this area also have relatively low kh (permeability–thickness product). Moreover, surface geothermal activity diminishes within this area. Thus, this area is a margin of the Kakkonda reservoir. However, note that the temperature of well(2) approaches ***300°C*** at the bottom.

As discussed above, temperature profiles of wells in and around the Kakkonda geothermal field gradually change from convective to conductive toward the southeast from the center of the development area. Thus, the shallow horizontal temperature distribution seems to decrease toward the southeast as seen in Fig.5. However, deep temperatures, such as that at 1,600m depth, exceed 300°C over the discussed area; even though it is 5km away from the center of the Kakkonda reservoir. The Kakkonda Granite is a heat source for the metamorphism of the Kakkonda reservoir as described above. However, because of its limited distribution and the characteristics of the temperature structure discussed above, the Kakkonda Granite alone cannot be the only heat source of this area. There should be more heat sources in this region. Therefore, the Kakkonda Granite is only one of the heat sources of this area and there must be other heat sources within this area.

THERMOLUMINESCENCE OF QUARTZ

Thermoluminescence (TL) of quartz has been utilized as one of the methods for dating of roch samples. However, paleodose declines according to temperature and its duration, so rbat results of TL dating in active geothermal fields sometimes give different ages even with samples from the same formation depending on geothermal activities of the locations of the samples (Takashima, 1985).

Tsuchiya et al. (1994) utilized this phenomenon as an indicator to estimate temperature and heat flow distribution in geothermal fields. They studied TL of quartz in volcanic and pyroclastic rocks in and around the Kakkonda area and found that total TL emission had no relation to the stratigraphic boundaries. Their result is shown in Fig.7. The area below the 5% of relative emission in Fig.7 (which was obtained by comparing with the totai emission of the reference sample collected from 10km away from the Kakkonda power plant), almost coincides with the development area for Kakkonda Units 1 and *2*. The area below the 40% of relative emission almost coincides with the area of sericite/montmorillonite mixed layer mineral zone. These results clearly suggest that TL of quartz from geothermal areas is applicable to the evaluation of thermal influence and io the estimation of subterranean heat sources in geothennal systems.

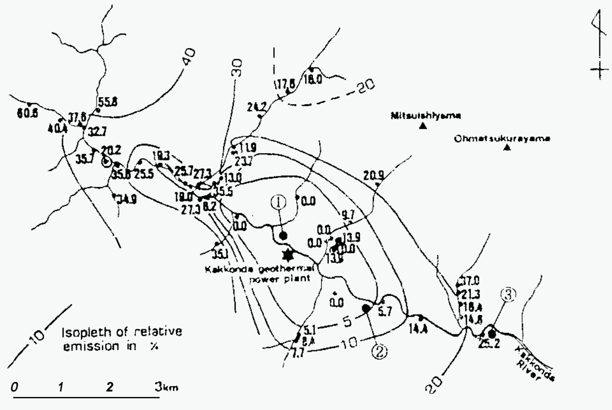

Fig.7 **Relative** emission **of** TL **of** quartz (Tsuchiya **et** al., 1994), **and** locations of **wells shown** in Fig.6.

Here we compare the result shown in Fig.7 with temperature distribution of Kakkonda as shown in Fig.6. In the center of the Kakkonda geothermal field, temperature profiles of wells are convective (e.g. well(1) in Fig.6). This area coincides with the zone within which the relative TL emission is less than 5%. This area also coincides with the area of surface geothermal activity as described above. Well(2) in Fig.6 is locaied at the margin of the reservoir so that its temperature profile is convective but slightly conductive, as described above. The relative TL emission exceeds 5% around the well(2) and increases toward the southeast, the lower reaches of the Kakkonda river. It reaches 25% at well(3) where the temperature profile is totally conductive. As discussed above, distribution of TL of quartz in volcanic and pyroclastic rocks in the Kakkonda area coincides well with surface geothermal activity and represents up flow of natural convection in the area. Thus, this method is useful to delineate up flow structure and surface boundary conditions of natural hydrothermal convection in geothermal systems. This is important for natural state modeling of geothermai reservoirs. Therefore, this method is useful especially in early stages of the geothermal development, although applicability to nther geothermal fields should be tested further and its fundamental theory should be further clarified.

Based on the up flow structure at the surface as discussed above, the total structure of the Kakkonda hydrothermal convection system is distributed along the Kakkonda river and its width perpendicular to the river is limited. This coincides with the distribution of fractured zones shown in Fig.4. Thus, the natural convection in Kakkonda is clearly controlled by this fracture distribution.

LOGGING AND WELL TEST DATA

Logging data of Well–13 and –19, typical deep production wells in Kakkonda, are shown in Fig.8. In Fig.8, static temperature of Well–18, an exploration well next to Well–19 in the same drilling pad, is also shown. As seen in Fig.8, temperature suddenly increase from about 1,000 to 1,500m depth and exceeds 300°C, indicating that there are two layers of hydrothermal convection; this high temperature zone is the deep reservoir. Since Well–19 is the most northwestern deep well and Well–13 is the most southeastern deep well in Kakkonda (c.f. Fig.3), the horizontal temperature distribution in the deep reservoir is thought to be almost homogeneous at about 350 to **360°C.**

Lost circulation records of Well–13 and –19 are also shown in Fig.8. As seen from those records, there are many lost circulation zones in the shallow reservoir (above 1,000 to 1,500m depth), but there are only a few lost circulation zones in the deep reservoir except at around the top of the Kakkonda Granite. This implies that average permeability of the shallow reservoir is much higher than that of the deep reservoir. We will discuss this difference in permeability later. As described by Kato and Doi (1993), the lost circulation at the top of the Kakkonda Granite occurs in most of the deep wells. Thus, the top of the Kakkonda Granite forms a vcn fractured permeable horizon and most of the deep wells produce geothermal fluids from the vicinity of the top of the pluton (Fig.8).

The kh (permeability–thickness product) of wells in the shallow reservoir is on the order of 10^{-12} to $10^{-11}m^3$ and that of wells in the deep reservoir is on the order of $10^{-12}m^3$ from single well tests. Also kh by pressure interference tests is on the order of $10^{-11}m^3$ in the shallow reservoir and about $10^{-12}m^3$ in the deep reservoir. Thus, the shallow reservoir is very permeable all over the reservoir. Wells in the shallow reservoir produce several tens of tons of steam per hour, and hot water at 6 times to 10 times greater, at well head pressures of several bars.

In contrast, the permeability of the deep reservoir is rather low except at the top of the Kakkonda Granite which is the only permeable horizon currently found in the deep reservoir. However, due to the high temperature anti high pressure in the deep reservoir and relatively high permeability at the top of the Kakkonda Granite, productivity of the deep wells is very high. Production is several tens to a hundred tons of steam per hour and about the same amount or less of hot water at well head pressures of about several tens of bars. The most important fractures for production in the deep reservoir are marginal ones at the top of the Kakkonda Granite and those in the Pre–Tertiary formation associated with intrusion of the Kakkonda Granite, but some minor fractures exist in the Tertiary formations in the deep reservoir.

RESERVOIR PRESSURE RESPONSE TO EXPLOITATION

Change of reservoir pressure profiles over 12 to 13 years of production in the Kakkonda shallow reservoir for the Unitl is shown in Fig.9. Note that the pressure of the shallow reservoir declined over this period, but its gradient did not change. This implies that permeability of the Kakkonda reservoir is high enough to homogeneously distribute the pressure change all over the reservoir. Also note that the pressures in the deep reservoir are on the line of current pressure of the shallow reservoir. Thus, the deep reservoir is hydraulically connected to the shallow reservoir, and is responding to the exploitation for the Unitl.

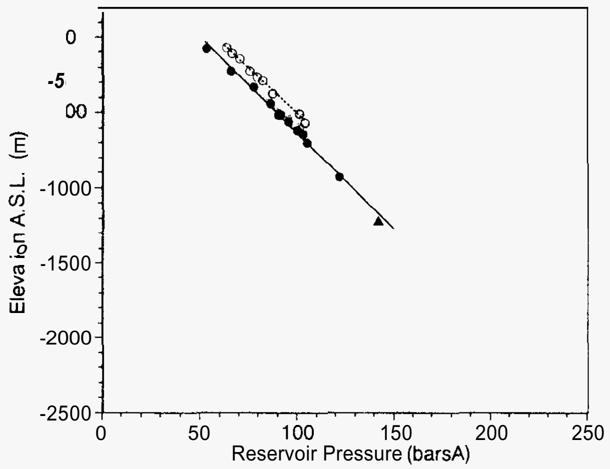

Fig.9 Reservoir pressure profile at Kakkonda (Hanano and Takanohashi, 1993). Solid circles and solid triangles are data of the shallow reservoir and the deep reservoir in 1990/1991, respectively. Open circles are data of the shallow reservoir in 1977/1978.

Fig.10 shows change of reservoir pressure observed at 3 monitor wells. As seen in Fig.10, the change of the reservoir pressure essentially stabilized at around 4 years of production, because of sufficient fluid recharge from the surrounding area.

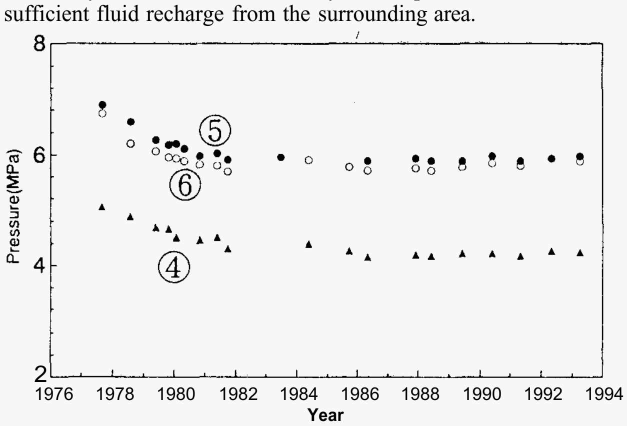

Fig.10 Change of reservoir pressure in Kakkonda at 3 monitor wells

PERMEABILITY STRUCTURE OF THE RESERVOIR

Natural hydrothermal convection in geothermal systems evolve when there are appropriate heat sources and permeability. Applying one-dimensional vertical advection model, Kajiwara et al. (1993) estimated macroscopic vertical reservoir permeability from temperature profiles in Kakkonda.

Velocity of steady ascending flow in homogeneous half-infinite porous medium can be estimated from the vertical temperature profile in the medium, when the hot water ascends homogeneously and one-dimensionally from the infinite depth to the ground surface on which the temperature is kept constant. According to Turcotte and Schubert (1982, p.401), the temperature T(K) of the depth y(m) is:

$$T=T_r-(T_r-T_0)\exp((\rho cv/\lambda)y) \qquad (1)$$

where T_r(K) is the temperature of the infinite depth, T_0(K) is the temperature at the ground surface, ρ(kg/m^3) is the density of fluid, c(J/kg·K) is the isobaric specific heat capacity of fluid, λ(W/m·K) is the thermal conductivity, and v(m/s) is the velocity of the ascending flow. Equation(1) can be reduced to the following form (e.g. Sakagawa et al., 1994).

$$\log(T_r-T)=(\rho cv\cdot\log(e)/\lambda)\cdot y+\log(T_r-T_0) \qquad (2)$$

Thus, when appropriate T_r is found, the relation of y and $\log(T_r-T)$ becomes linear, so that the ascending velocity v can be estimated from the slope of the graph. Applying **Darcy's** law, macroscopic vertical permeability k_z can be estimated using the reservoir pressure gradient. Fig.11 is an example in Kakkonda. In this case v is approximately **6×10^{-9}m/s** and k_z is **$9\times10^{-15}m^2$**.

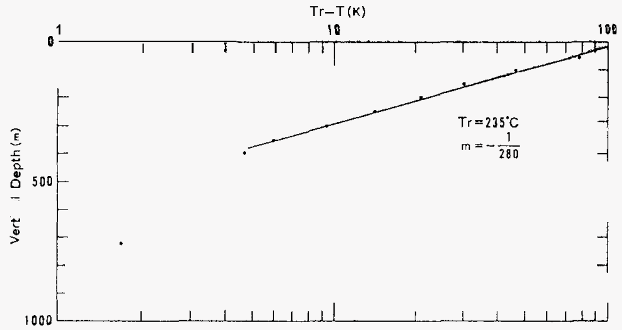

Fig.11 Analysis of a temperature profile of a well in the shallow reservoir (Kajiwara et al., 1993).

Using this method, the average k_z of the shallow reservoir and deep reservoir are estimated to be approximately $10^{-14}m^2$ and $10^{-16}m^2$, respectively (Kajiwara et al., 1993). However, based on a linear stability analysis accounting for the effect of high temperature, this value for the deep reservoir is very close to the minimum critical permeability for the onset of natural convection in the deep reservoir. Thus, the hydrothermal convection in the deep reservoir evolved at very critical hydrothermal conditions.

MICRO-EARTHQUAKES

Geothermal reservoirs are characterized by their abundant fractures and hot fluid. Thus, characteristic micro-earthquake activities are sometimes observed in geothermal fields. Micro-earthquake observation in Kakkonda has been conducted continuously by Geological Survey of Japan (e.g. Tosha et al., 1993). Epicenters of micro-earthquakes observed in Kakkonda in 1988 are shown in Fig.12. As seen in Fig.12, horizontal distribution of the micro-earthquakes in Kakkonda coincides with the fracture distribution shown in Fig.4. Moreover, the lower boundary of vertical distribution of the micro-earthquakes also coincides with the top of the Kakkonda Granite (Fig.13). Thus, the micro-earthquake hypocenter distribution in Kakkonda well agrees with three-dimensional distribution of the permeable zone.

Based on the micro-earthquake hypocenter distribution, the up flow zone into the deep reservoir from great depth was estimated (e.g. Sugihara, 1993). Fig.14 shows change of hypocenter distribution during build-up of wells for power plant inspection. As seen in Fig.14, micro-earthquakes first occurred around the production wells. Then the distribution expanded in two directions; towards shallow reinjection wells and the very deep part of the reservoir to the northwest. Micro-earthquakes are induced by an increase in pore pressure and the pressure build-up expands towards fluid **sources.** Thus, these ***two*** directions of expansion of the hypocenter distribution represent fluid sources in the Kakkonda reservoir; the one towards the deep zone in the northwest represents the flow path of hot up flow from great depth. The up flow zone estimated from micro-earthquake data coincides with that estimated from the distribution of anhydrite as discussed before.

CONCLUSIONS *AND* SUGGESTIONS FOR FURTHER STUDY

(1) Hydrothermal convection in the Kakkonda geothermal area evolved within a tectonically controlled fractured zone. The neo-granitic pluton (Kakkonda Granite) found by drilling of deep wells is the heat source for the metamorphism in the Kakkonda reservoir. However, in accord with the regional temperature distribution, the

high temperature zone is horizontally much wider than the fractured zone. Thus, there are additional heat sources in this region.

(2) There are two reservoirs with different temperature and permeability; the shallow reservoir with average temperature of **230** to **260°C** and average permeability of the order of $10^{-14}m^2$, and the deep reservoir with average temperature of **350** to **360°C** and average permeability of the order of $10^{-16}m^2$. The micro-earthquake study revealed that the up flow into the reservoir comes from great depth from the northwestern part of the reservoir.

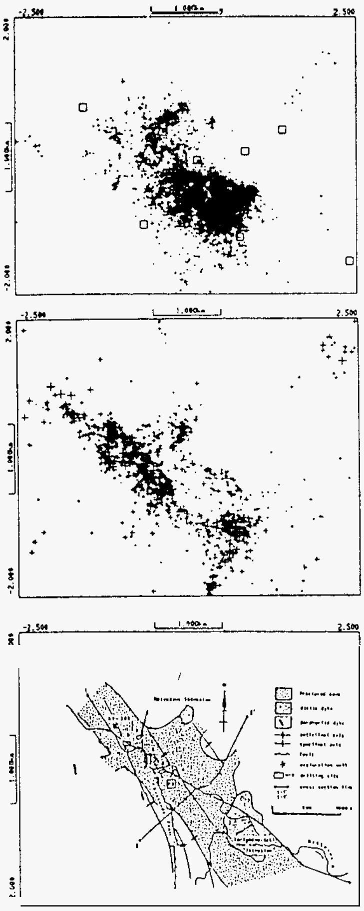

Fig.12 Epicenter distribution at Kakkonda in 1988 (Sugihara et al., 1989). (a): shallower than -1km sea level, open squares are micro-earthquake observatories (b): deeper than -1km sea level, (c): Fracture distribution (same as Fig.4; Doi et **al.**, 1988).

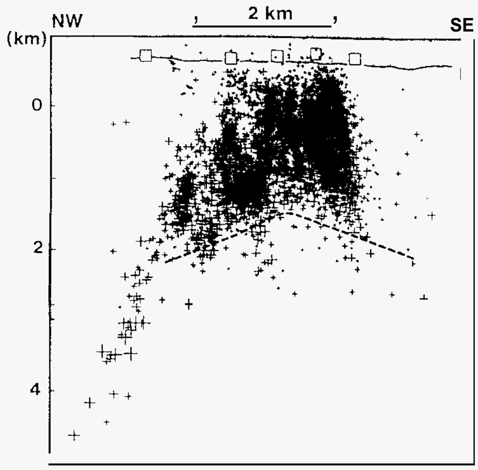

Fig.13 Hypocenter distribution at Kakkonda in 1988 (Sugihara, 1993). open square: micro-earthquake observatory. Dashed line: top of neo-granitic pluton (Kakkonda Granite) (modified from Kato et al., 1993).

(3) A Study **of** recharge zones by **use** of such methods as: stable isotopes, pressure interference tests between the deep and shallow reservoir, and pressure response tests on the deep reservoir is suggested. Also, modeling of the natural state of fluid circulation that includes cooling of the magmatic inttusives following intrusion are tasks needed in the future in order to understand the complete picture of the Kakkonda hydrothermal system.

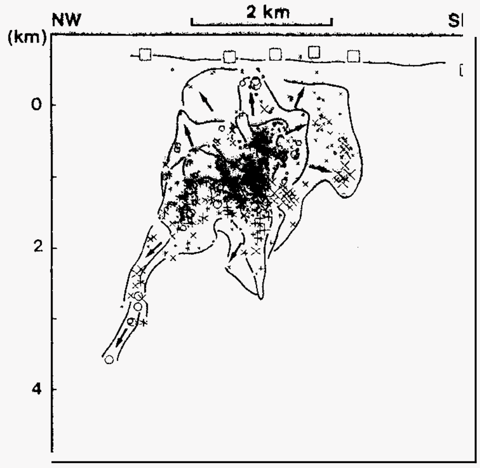

Fig.14 Expansion of hypocenters during pressure build-up in lune 1988 (Sugihara, 1993; Tosha et **al.**, 1993). +: The first day of build-up, *: the second day, **O**: the third day, x: 4th to 7th days.

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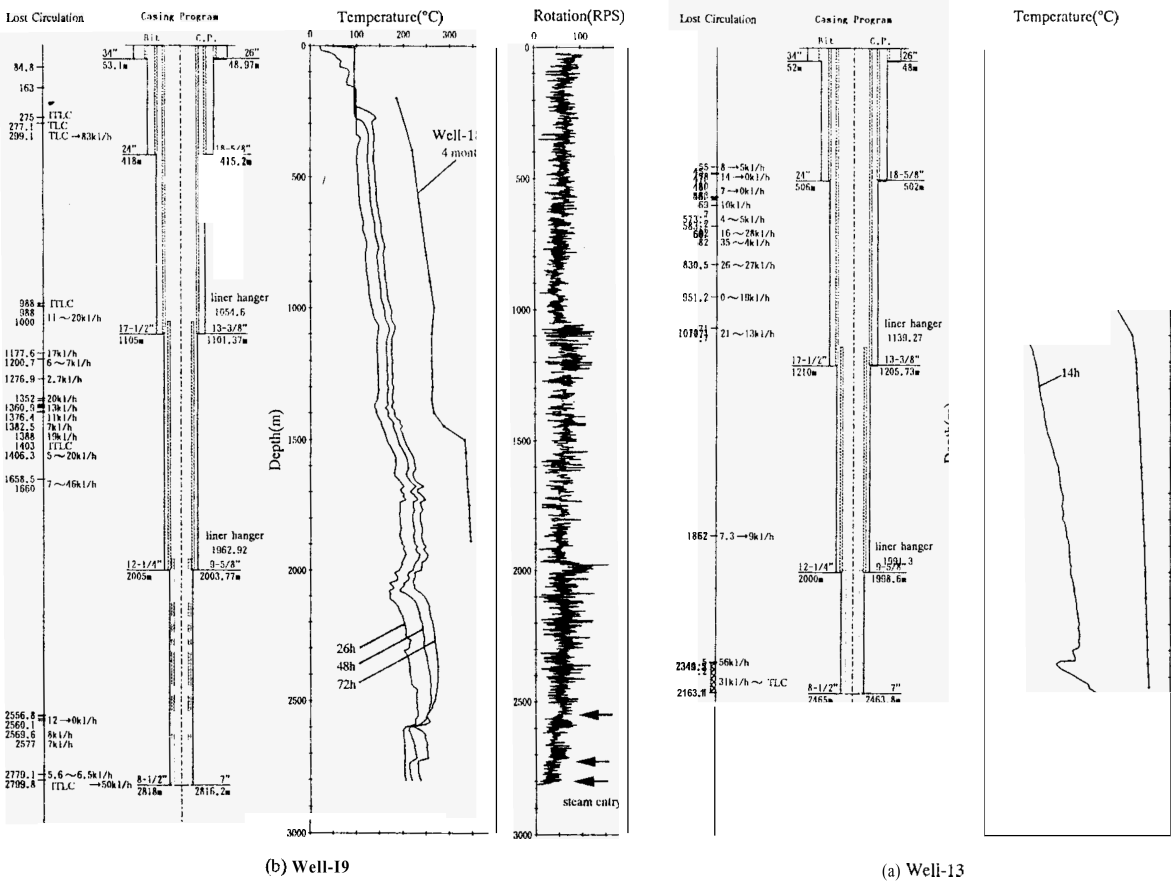

Fig.8 Logging and lost circulation data of Well-13 and -19. TLC: total lost circulation, ITLC: instantaneous total lost circulation.