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RECENT RESULTS OF NEDO "DEEP-SEATED GEOTHERMAL RESOURCES SURVEY" PROJECT

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SUMMARY - The well WD-lb, which was drilled in the Kakkonda field for the NEDO deep-seated geothermal resources survey project, produces fluids from a deep reservoir. The well's total flow rate of is about 10 tons/hour at 3 bars wellhead pressure. Total discharge enthalpies are as high as 2,500kJ/kg, suggesting that a two-phase feed condition developed in the deep reservoir. The chemical characteristics of the water of well WD-lb are similar to those of the other deep production wells in Kakkonda. The results at Kakkonda will be used to make guidelines for the development of deep-seated geothermal resources. In order to investigate the geothermal industry's technological needs for development of deep-seated geothermal resources, interviews with representatives of the industry were held.

1. INTRODUCTION

Most geothermal power plants have been using resources in shallow reservoirs at depths less than 2,000m in Japan. In some fields, geothermal resources also exist at depths over 2,000m. Therefore, deep-seated geothermal resources, occurring in the basement and intrusive rocks underneath already-exploited shallow reservoirs, will help increase and maintain the power plant output. However, exploration, drilling and production technologies have not yet reached the level that make development of the high temperature deep-seated resources economically feasible.

With this background, NEDO started a research project named "Deep-seated Geothermal Resources Survey" in 1992, in order to clarify the anatomy of the entire geothermal system from its deep heat source to its shallow reservoirs, and in order to test application of the conventional technologies.

The Kakkonda geothermal field in northern Honshu was selected as the site for this project. NEDO drilled two wells, WD-la and WD-lb, for geothermal survey in Kakkonda (Figure 1). Prior to this project, a large body of data on the shallow reservoir had been accumulated during the development of the first power plant, Kakkonda Unit 1 (50MW), which has been in operation since 1978. In addition, an outline of the deep-seated geothermal resources around the Quaternary granite had been obtained during the deep drilling conducted by 1992. The second power plant, Kakkonda Unit 2 (30MW) started operation in 1996. The unit has operated using the steam produced mainly from the deep reservoir.

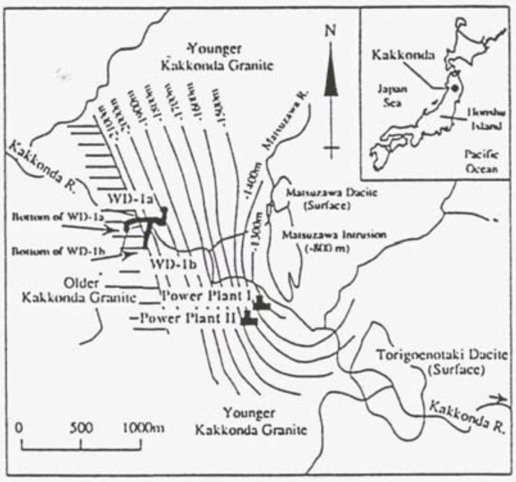


Figure 1- Location of the Kakkonda geothermal field, the trace of WD-la and WD-lb, and contours of the top of the Kakkonda granitic pluton at depths in meters below sea level (modified from Doi et al., 1995)

2. REVIEW OF THE PROJECT

The progress of this project was reported by Yagi et al.(1995); Uchida et al.(1996); and Kamenosono et al.(1997). The following is a review of these reports.

2.1 Drilling history of WD-1a and WD-1b

Drilling of WD-la started in January 1994 and reached a depth of 3,729m in July 1995. A top drive drilling system was used for drilling at depths below 1,500m. WD-1a encountered Quaternary granite at a depth of 2,860m, and penetrated for about 870m into the **granite.**

Since WD-la did not encounter a productive reservoir in the vicinity of the granite, WD-lb was drilled as a side track well of WD-la. Drilling of WD-1b started in September 1996. Trajectory correction for a southward direction was carried out using a positive displacement motor tool and *gyro* measurements. Lost circulation began when WD- lb reached a depth of 2,478m, and it grew to a total lost circulation. Therefore, drilling was continued to a depth of 2,963m without return of mud. WD-lb encountered the Quaternary granite at a depth of 2,816m; here some productive fractures were found.

The distance between the bottom of WD-lb to WD-la is less than 200m (Figure 2). However, only WD-1b hit fractures with large lost circulations in the vicinity of the granite. This shows that fiactures of high permeability exist in the vicinity of the Kakkonda granite (Kamenosono et al., 1997).

2.2 Clarification of heat source and transition of heat structure

Temperature recovery tests at WD-la were carried out using melting tablets made fiom metal compounds and conventional logging tools (Figure 3). The melting tablets showed that the bottom hole temperature was over 500°C after 159 hours standing time. This suggests that the Quaternary granite is the heat source of the Kakkonda geothermal system. The **sudden** change in temperature gradient around 3,100m depth (corresponding to the temperature of 380°C) indicates the transition of the thermal structure. Hydrothermal convection occurs at depths shallower than 3,100m, however heat conduction may dominate below this depth (Ikeuchi et al., 1996).

2 3 Application of the drilling technologies

WD-la reached the depth of 3,729m, where the bottom hole static temperature **was** more than 500 "C. Trajectory correction runs **using** a positive displacement motor tool were carried out successfully where the formation temperature was higher than 350°C during the drilling of WD-lb. *An* appropriate mud cooling system and a top-drive system *to* cool the bottom hole assembly continuously while running every drill pipe stand in the hole were the key to overcome the high temperature environment (Saito et al.,1997).

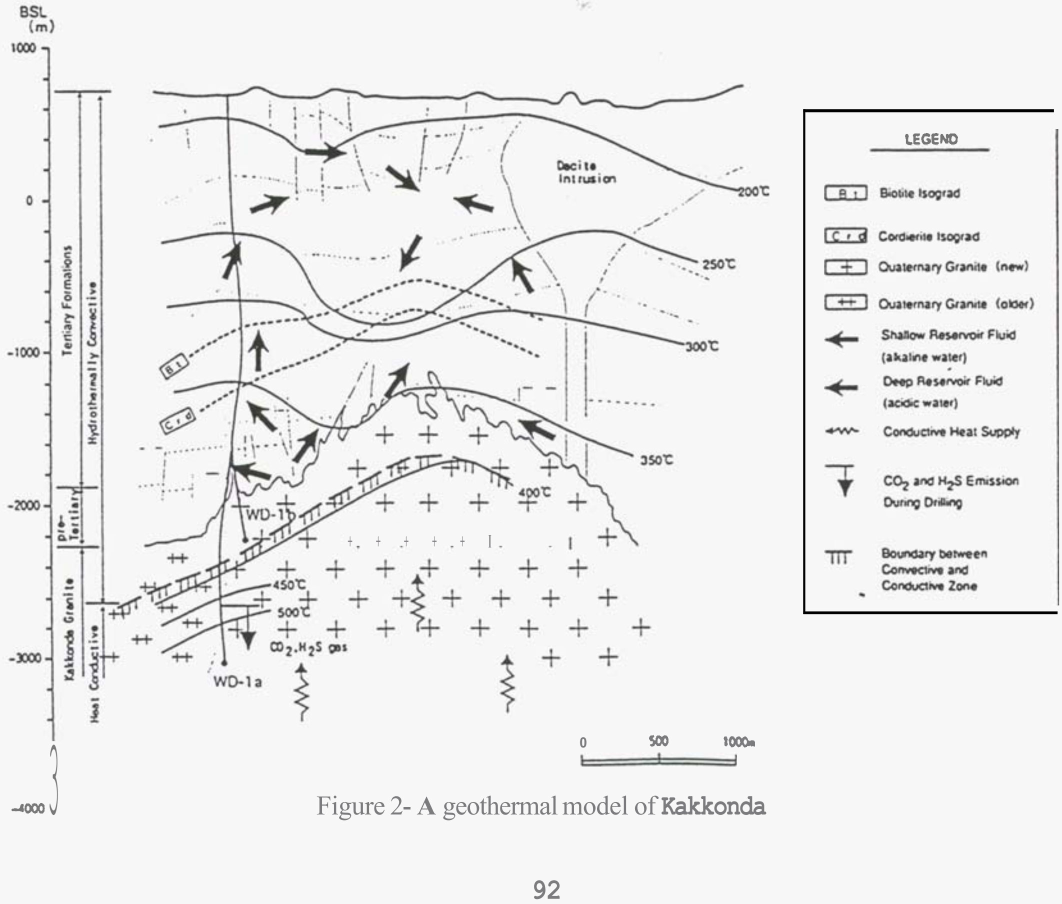


Figure 2- A geothermal model of Kakkonda

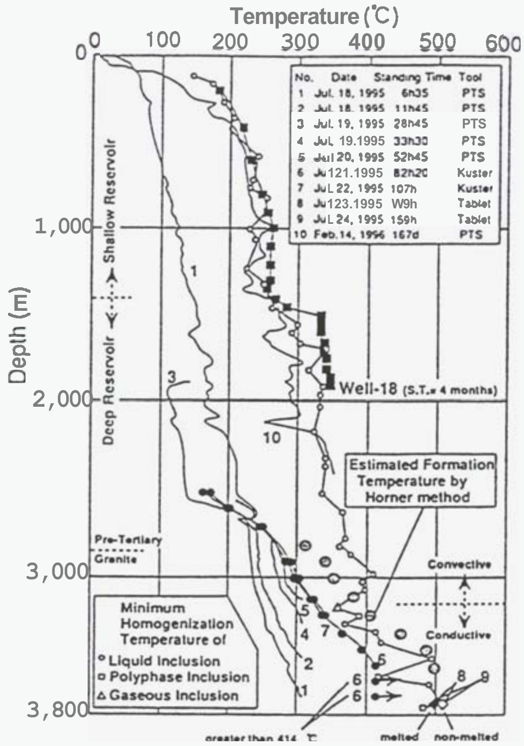
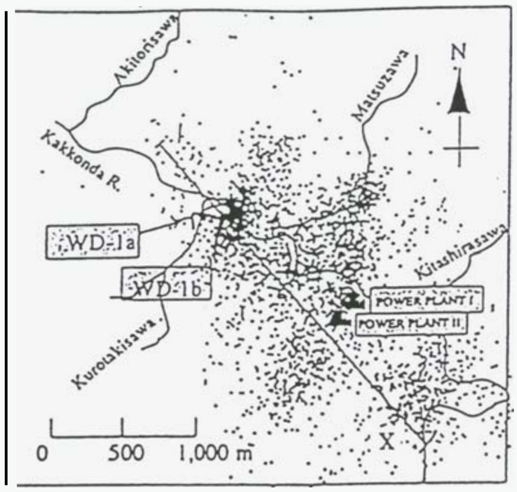


Figure **3-** Results of temperature recovery measurements and estimated formation temperature by Homer extrapolations. Minimum homogenization temperatures of fluid inclusions from cores and cuttings, and a temperature profile of Well-18, near WD-la, are also shown.

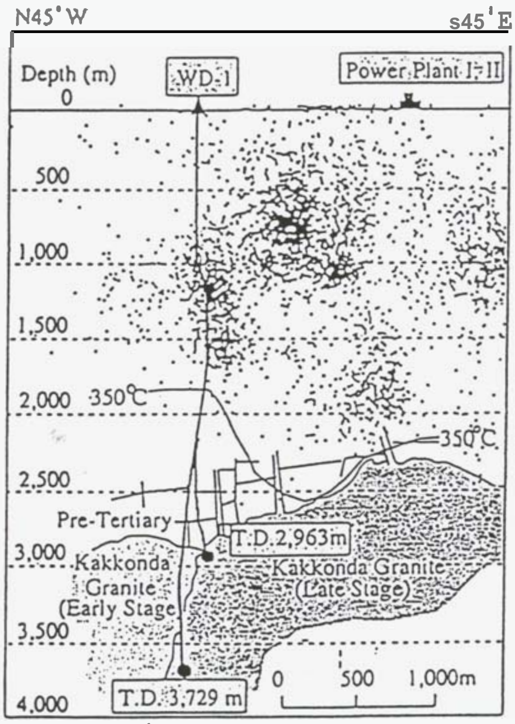
2.4 Application of the exploration methods

Micro-earthauake monitoring- Micro-earthquakes have been monitored at ten seismometer stations since January 1995. The hypocenters form swarms which are **NE-SW** trending and extend deeper toward the west on the cross section (Figure **4).** The trace of WD-la goes outside of the swarms, while that **of** WD-lb goes towards the swarms. Consequently, only WD-lb hit the deep reservoir. It is believed that productive zones exist under the swarms of micro-earthquake hypocenters (Uchida et al., 1996).

Resistivity *survey-* Natural source magnetotelluric method **(MT)** and controlled-source magnetotelluric method (CSMT) were applied for measuring resistivity, and subsequent two-dimensional **(2-D)** inversions were performed. The 2-D resistivity models show the shape of the granite as a high resistivity zone. Also, there is another large resistivity body in the northwestern side of the field, where WD-la was targeted and failed to intersect productive fractures. WD-lb was drilled toward to the boundary between the conductive zone and the resistive one, and hit the deep reservoir (Kamonosono et al., 1997).



(A) A plan view



(B) a cross section along the line X

Figure **4-** Distribution of micro-earthquake hypocenteres obtained during fiscal year 1995; **(A)** a plan view and (B) a cross section along the line X

Fracture Analysis- The Formation Micro Imager logging (FMI; trademark of Schlumberger) was carried out at depths between 60m and 2,635m in WD-la and 2,254m and 2,910m in WD-lb. Therefore the FMI image in the pre-Tertiary formations and Kakkonda granite was obtained only in WD-1b. The frequency of the fiactures detected by FMI is largest in the Tertiary (Miocene) formations **(4.7-7.8** fractures/m), followed by the pre-Tertiary (1.6-4.0 fractures/m) and the granite (0.5 fractures/m). Many fiactures having N0°-90°E strikes and dipping steeply northwestward are observed in the Tertiary formation in WD-lb, whereas fractures of the same type are rare in WD-la. It is possible that these fi-actures contribute to the permeability contrast between WD-la and WD-lb. Drilling-induced tensile fi-actures (DTF), which are caused by the pressure of mud and thermal stress during drilling, were also detected in the FMI images. The DTFs were formed on the wall in N60°-90°E direction in both WD-la and WD-lb. It suggests that the horizontal maximum stress axis is in this direction from the surface to the Kakkonda granite (Kato et al., 1995; Doi et al., 1997).

3. ON-GOING RESEARCH

31 Production test

After logging in WD-lb, the drill string was stuck at a depth of 2,870m, 93m above the bottom, in March 1997. Much recovery work **was** performed to **free** the string, but in vain. Finally the string was backed off at a depth of 2,633m, and the string below was left in the well. A slotted liner **was** run and set at a depth **of** 2,630m. **As** damage had been found **on** the 9-5/8" casing at depths between 1,400 and 1,700m, a 7" scab liner was set at depths between 1,203m to 2,126m.

A 3-month long production test of WD-lb started in **June** 1998. Spinner logging during the production test showed that most of the fluid inflow was from the formations at depths below 2,633m. Figure 5 shows the results of the production test. The flow rate of steam was stable except in the early stage of the test, and it was around 7 tonshour at 3 bars wellhead pressure. The flow rate of liquid **was** 1.5 tonshour **on** the average, however it fluctuated. The calculated total discharge enthalpies are scattered around 2,500kJ/kg **as** a consequence of the variations of the water flow rate. These values are much greater than the liquid phase enthalpy (1,672kJ/kg) at the reservoir temperature of about 350°C. This indicates that a two-phase feed condition (i.e. excess enthalpy) has developed in the reservoir as it has in the other deep production wells in Kakkonda. Total flow rate of WD-lb is less than 10 tons/hour. However, the injectivity of over 100 tonshour **was** confirmed before the production test. To understand the difference between the flow rate and the injectivity, the following effects should be investigated; the decline of the reservoir pressure due to the production for the power **plants;** low permeability (kh) of WD-lb as compared with the other production wells; and the effect of formation collapse and drill string left at depths below 2,633m.

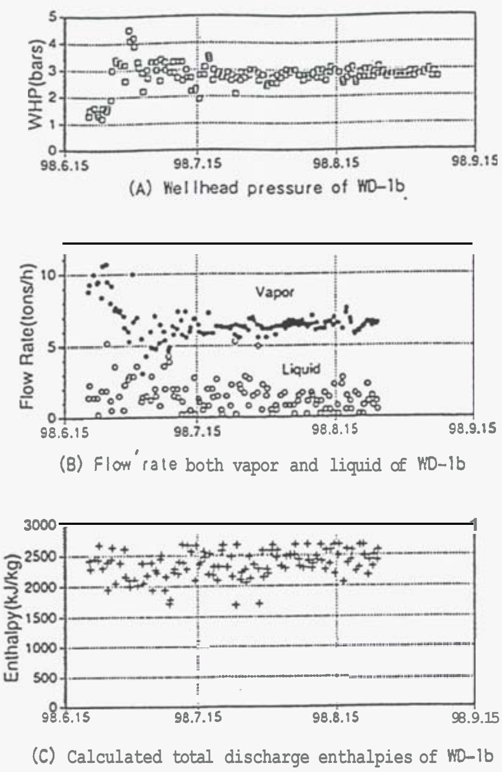


Figure 5- Results of the production test; **(A)** changes in wellhead pressure of WD-lb; **(B)** changes in flow rate both vapor and liquid of WD-lb; (C) changes in calculated total discharge enthalpies of WD- lb

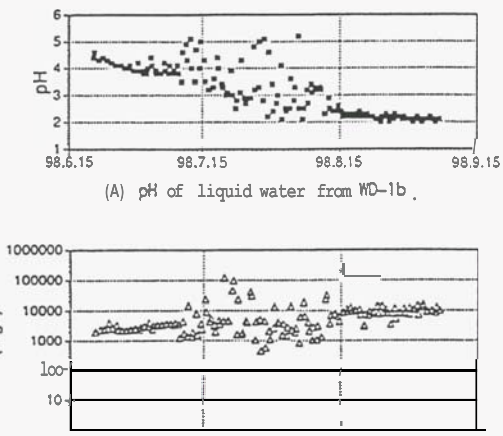


Figure 6- Results of fluid chemistry monitoring; (A) changes in pH of liquid water from WD-lb; (B) changes in Cl concentrations of liquid water from WD-1b

Table 1- Technological needs for development of deep-seated geothermal resources

Exploration and investigation methods	Electromagnetic methods Seismic exploration methods
Drilling and production technologies	Technologies to prevent scaling Stimulation technologies for permeability improvement
Integrated analysis and modeling	Fractures and reservoir characteristics Physical and chemical processes of geothermal fluids (including acid water) Reservoir evaluation technologies

3.2 Fluid Chemistry Monitoring

Chemical compositions of the fluids discharged fi-om WD-lb have been continuously monitored during the production test. The pH values of the liquid waters after vapor separation at atomospheric pressure decreased with time and became almost steady at around 2.3. The Cl concentrations of the liquid waters ranged fiom the order of 1,000 mg/l to 100,000 mg/l. These changes are probably due to the changes in the fluid flow conditions (Figure *6)*.

Yanagiya et al. (1996) reported that the shallow production wells in Kakkonda discharge slightly alkaline (pH = 8-9) waters, whereas the waters from the deep wells are acidic (pH = 3.2-4.5). They also stated that the deep waters have larger Cl, Mg and Fe concentrations than those in the shallow waters. Though the pH of the liquid waters from WD-lb is lower than that of the other deep wells in Kakkonda, the chemical characteristics of the waters fi-om WD-1b are similar to those of the other deep production wells.

Akaku et al. (1997) pointed out that the addition of a small amount **of** HCl could explain the acidity **of** the water fiom the Kakkonda deep wells. However, the deepest well, WD-la, did not indicate the existence of HCl in the Kakkonda Quaternary granite. The alteration mineral assemblage in the deep reservoir also argues against HCl supply fi-om depths. More research work is believed to be necessary in order to clarify the source of acidity of the Kakkonda deep water.

3 3 Reservoir Evaluation

Changes in the reservoir pressure have been monitored in five shallow wells at depths from 590m to 1,270m since March 1996. Declining pressure in the shallow reservoir was observed. It is believed that this occurred because of steam production **fiom** deep and shallow production wells for the power plants.
Pressure monitoring in the deep reservoir will be started in WD-lb, after the production test is finished. The reservoir data obtained through the pressure monitoring, production test and well test analysis will be used for reservoir simulation studies.

3.4 Application of the Kakkonda Results to Other Geothermal Fields

The-results of the project at Kakkonda will include an integrated geothermal model and test the application of conventional technologies for development of deep-seated geothermal resources. In addition, a guideline for the development of deep-seated geothermal resources will be made based on the Kakkonda results and information from other geotheml fields.

In preparation for making the guideline, representatives of the Japanese geothermal industry were interviewed in order to assess the interest in the development of deep geothermal resources and related technological requirements. The findings of the interviews are summarized as follows.

Since there is insufficient data regarding the potential of deep geothermal resources, it is difficult for them to estimate the amount of the geothermal energy and the cost of the development **of** deep-seated resources. Therefore, the exploitation of deep resources will begin when the production fi-om shallow reservoirs fails to maintain *full* output in their power plants. Table 1 shows technologies which they expect to be further improved or well developed to reduce the risk for the development of deep-seated geothermal resources.

4. CONCLUSIONS

During the production test, the steam flow rate of WD-lb was stable around 7 tonshour at **3** bars wellhead pressure, whereas the liquid flow rate was **1.5tons/hour on** the average and scatters. The calculated total discharge enthalpies were around **2,500kJ/kg**, and is much greater than the liquid phase enthalpy at reservoir temperature. This indicates that two-phase feed condition may develop m the deep reservoir.

The pH **of** the liquid water from WD-1b decreased to 2.3, **and** the Cl concentrations **of** the liquid waters ranged from the order **of** 1,000mg/l to 100,000mg/l. The chemical characteristics of the waters from WD-1b are similar to those of the other deep production wells in **Kakkonda.**

Declining pressure in the shallow reservoir was observed. It is believed that this occurred because of steam production from deep and shallow production wells for the power plants. Pressure monitoring in the deep reservoir will be started in WD-1b after the production test is finished. The reservoir data obtained through the pressure monitoring, production test and well test analysis will be used for reservoir simulation studies.

A guideline for the development of deep-seated geothermal resources will be made based on the **Kakkonda** results and information from other geothermal fields. In order to investigate the technological needs for the development of deep geothermal resources, the geothermal industry was interviewed.

5. ACKNOWLEDGMENTS

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