DEEP GEOTHERMAL RESOURCES SURVEY PROJECT IN THE KAKKONDA GEOTHERMAL FIELD

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ABSTRACT

The New Energy and Industrial Technology Development Organization (NEDO) has been conducting a research project named "Deep-Seated Geothermal Resources Survey" since 1992 in order to establish a desirable direction for development of deep geothermal resources which exist beneath the already-developed shallow reservoirs. A deep drillhole, WD-1, has been drilled in the Kakkonda geothermal field in northern Japan. WD-1 reached a depth of 3,729 m in July 1995 by applying the latest drilling techniques such as top-drive drilling system, enabling the collection of highly valuable information for understanding the characteristics of deep geothermal system.

Quaternary granite, considered to be a possible heat source, was encountered at depths of over 2,860 m. The borehole was drilled into the granite for a length of 870 m to determine the thermal structure and deep fracture systems. Although we did not encounter major lost-circulations during drilling in the granite, we confirmed a temperature greater than 500 °C at the bottom of the hole. The recovered temperature profile suggests a drastic change from hydrothermally convective zone to thermally conductive zone at a depth of approximately 3,100 m. This implies the existence of the bottom of hydrothermal convection system at this depth. Borehole fluid sampling was carried out for geochemical investigation after the temperature recovery measurement, and extremely saline hydrothermal fluids were collected near the bottom of WD-1.

Side-track drilling of WD-1 was started from a depth of 2,200 m in September 1996, targeting productive fractures expected near the boundary of the granite in a depth range from 2,800 to 3,000 m. We successfully encountered large lost-circulation at some depths, and the side-track drilling was terminated at a depth of 2,963 m in January 1997. The well is now in a process of various loggings, and we expect a production test in early summer 1997.

INTRODUCTION

The utilization of deep geothermal resources is an important subject for maintaining and increasing power generating capacity of already-developed geothermal fields. NEDO has been conducting a research project named "Deep-Seated Geothermal Resources Survey" since 1992 under the New Sunshine Project of the Ministry of International Trade and Industry (MITI). The research project aims to investigate the characteristics of deep geothermal systems and evaluate the possibility of utilizing deep geothermal fluids which exist beneath the exploited shallow reservoirs (Uchida et al., 1996). In this project, NEDO has been drilling a 4,000 m class well, WD-1, in the Kakkonda geothermal field, northern Honshu Island, where a liquid-dominated geothermal system has been utilized for power

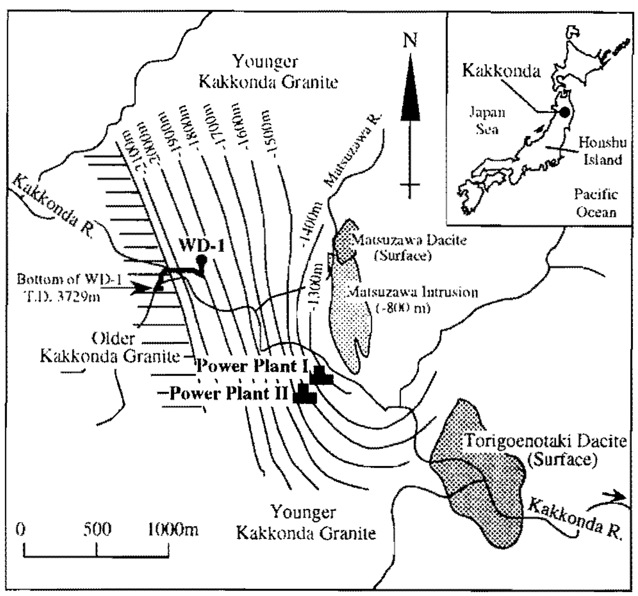

Fig. 1. *Location of the Kakkonda geothermal field, the trace of WD-1a, and contours of the top of the Kakkonda granitic pluton at depths in meters below sea level (reproduced from Doi et al., 1995).*

generation of 80 MWe (Fig. 1).

Three factors essential for understanding geothermal resources, namely, heat supply, fracture systems which form reservoirs, and hydrothermal fluid circulation, have been investigated to establish a geothermal model including deep and shallow structures. The project has four major objectives; to delineate deep geothermal systems including shallow ones; to develop new exploration tools for deep reservoir; to evaluate and systematize drilling technologies for deep geothermal drilling; and to examine materials applicable to produce deep hydrothermal fluids using corrosion and erosion tests. The final goal of the project is to establish recommended technological guidelines for development of deep geothermal resources in order to reduce risk of exploitation and to put deep geothermal energy into practical use.

Drilling of WD-1 has been carried out in two stages. The first one is to drill a main well, WD-1a, which reached a depth of 3,729 m in July 1995. The second stage is to drill a side-track well, WD-1b, from a depth of 2,200 m to 3,000 m. The field operation of the second one was started in September 1996 and is still going on. In this report, we will mainly describe the results obtained from the first stage of the work.

DRILLING PROCEDURE OF WD-1a

A drilling chart of the well WD-1a is shown in Fig. 2 along with the events which occurred during the drilling. The top-drive drilling system (TDS) and a mud cooling system were applied at depths greater than 1,500 m in order to cool the borehole effectively and reduce the risk for stuck of drill-strings.

A large amount of lost-circulations occurred at a depth range between 1,600 m and 2,150 m, where a shallow reservoir exists. A lost-circulation drilling was applied until a depth of 2,550 m, and PTS logging was then carried out to identify depths of the lost-circulations. Two-stage cementing was successfully performed to set a 9 5/8" liner-hanger casing to the depth of 2,550 m.

WD-1a hit a granitic formation at a depth of 2,860 m, however, we did not encounter large lost circulation which we had expected near the boundary of the granite. The drilling was further continued to investigate the inner structure of the granite, and reached a depth of 3,729 m in July 1995 with an 8 1/2" hole. At depths greater than 3,642 m, the circulating mud with high H_2S content started to return to the surface. A closed injection system was adopted so that the mud would not be directly exposed to the atmosphere. However, drilling operation was consequently terminated because of safety concerns when WD-1a reached a depth of 3,729 m. After various loggings and borehole fluid sampling were carried out for a couple of months, WD-1a was plugged back to a depth of 2,400 m to prevent ejection of H_2S gas.

Top-drive drilling coupled with mud cooling system has the advantage of lowering the temperature of boreholes very efficiently. By circulating mud water during the lowering of drill-strings, increase of the temperature in borehole can be minimized, and it sometimes makes the life of bits 10 times longer than a case when top-drive drilling is not applied. We have confirmed these merits of the TDS through the drilling of very high temperature formation. Also, we applied trajectory correction runs using a downhole motor (DHM) and a measurement-while-drilling (MWD) tool under high temperature environment. This was enabled by the use of the top drive system.

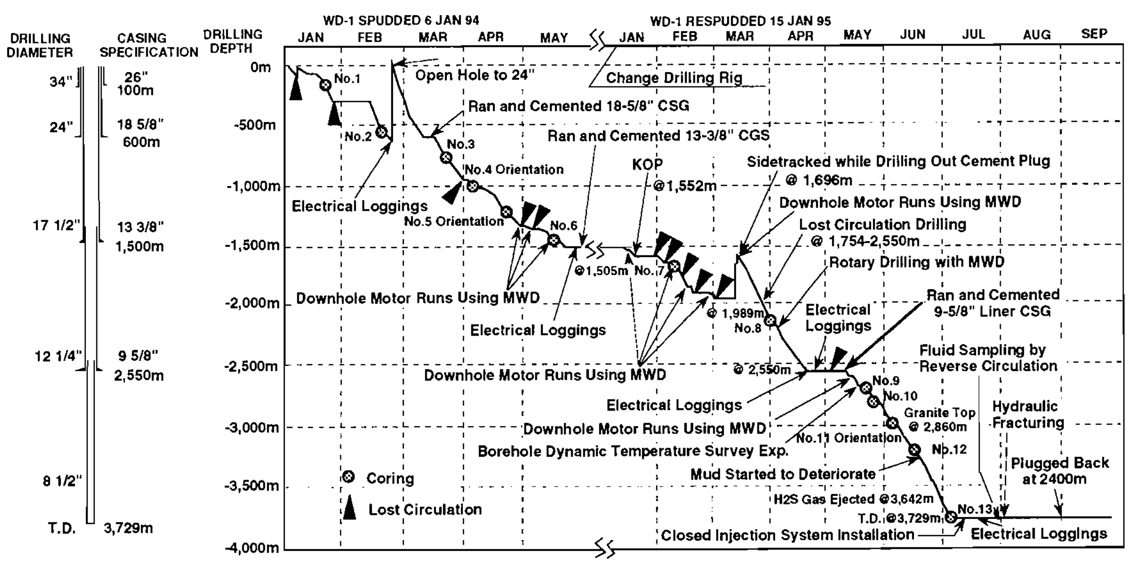

Fig. 2. Drilling chart of WD-1a.

GEOLOGY AND ALTERATION

Three oriented cores and ten non-oriented cores were collected at various depths down to 3,729 m, and cuttings were sampled every 5 m. A simplified geology of WD-1a is shown in Fig. 3. Major geological units observed from the surface are; Tertiary formations (Yamatsuda, Takinoue-onsen, Kunimitoge and Obonai Formations) composed of andesite/dacite lapilli tuffs, tuffaceous sandstone and black shale; pre-Tertiary formations composed of andesitic tuffs, shale and sandstone; and a Quaternary granite (Kakkonda Granite). The depth of the boundary between Tertiary and Pre-Tertiary formations in WD-1a is 2,660 m. The Quaternary granite was encountered at a depth of 2,860 m. The Tertiary formations have undergone intensive hydrothermal alteration, while the Pre-Tertiary formations have weak alteration. Several metamorphic minerals were observed in Tertiary and Pre-Tertiary formations. The first appearance of these minerals such as biotite, cordierite, anthophyllite and clinopyroxene, which were found at depths of 1,610 m, 2,020 m, 2,140 m and 2,860 m, respectively, was helpful in predicting the depth of the granite.

Kakkonda Granite is divided into three types, from shallow to deep: biotite-hornblende granodiorite, biotite-hornblende tonalite and clinopyroxene-bearing biotite-hornblende tonalite. The first two are examined to have undergone metamorphism, based on the fact that recrystallized biotite as pseudomorph of mafic minerals were observed. The deepest one is fresh petrographically and has not undergone either metamorphism or hydrothermal alteration. Therefore, its intrusion is considered to be a recent one. The K-Ar ages of common hornblende, biotite and potash-feldspar separated from the granite ranges from 0.34 to 0.05 Ma, from 0.48 to 0.02 Ma, and from 0.16 to 0.01 Ma, respectively (Kanisawa et al., 1994; NEDO, 1997). Here, we have to notice that several samples used for dating were collected at depths where formation temperature exceeds closure temperatures of the minerals.

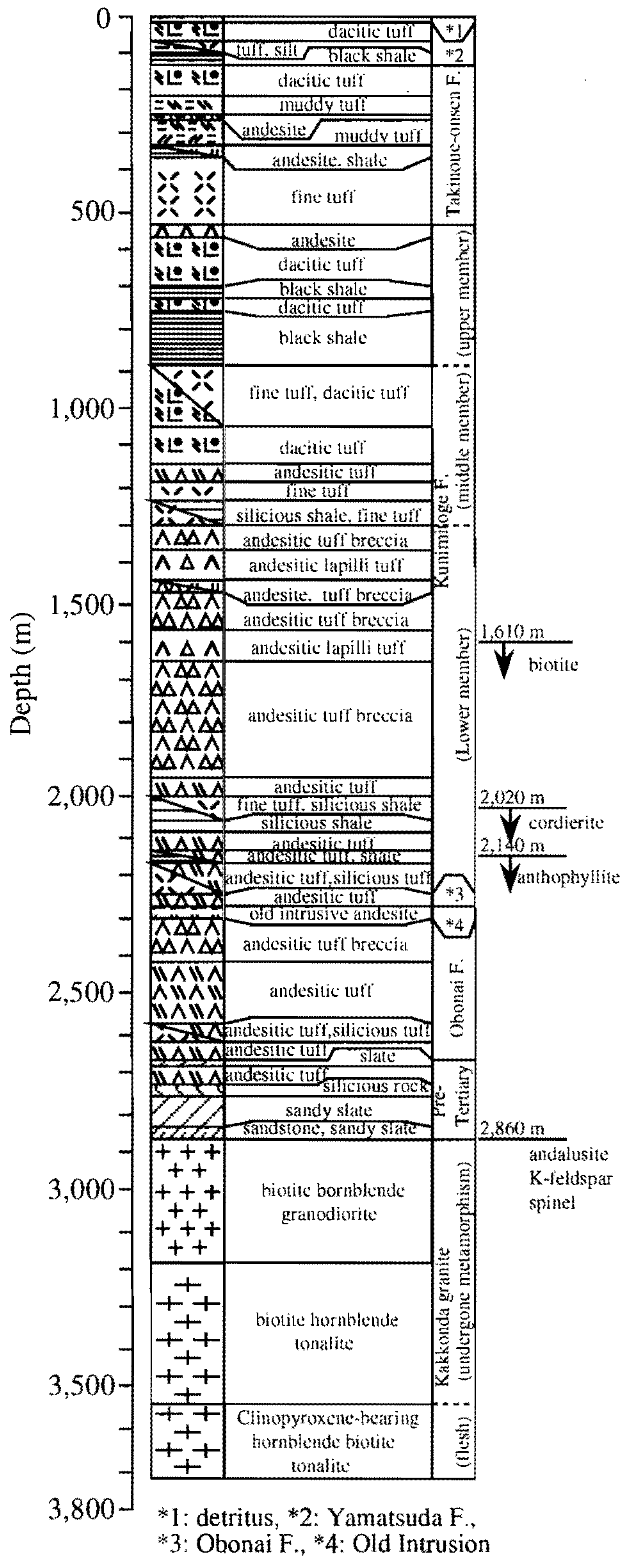

Fig. 3. Simplified geologic column of WD-1a and the first disappearance depths of metamorphic minerals during the drilling.

FRACTURE ANALYSIS BY LOGGING DATA

Loggings applied in WD-1a are as follows: temperature logging, normal resistivity logging, *Formation Micro Imager (FMI), *Dual Latero-Log, *Dipole Shear-Sonic Imager, *Litho Density Logging, and natural gamma-ray logging (*trade-mark of Schlumberger). Because of the rapid recovery of the temperature in WD-1a, which was due to no lost-circulation, and because of the caving which occurred around a depth of 2,650 m, these loggings were performed only up to a depth of 2,650 m with the exception of temperature and normal resistivity loggings, which were run to the bottom of the well.

Fracture analyses of the FMI logging data revealed that low dip angle fractures are dominant at depths greater than 1,500 m. However, a number of NE-trending fractures with high angle dipping to SE were observed at depths between 2,570 and 2,650 m. At depths less than 1,500 m, where the shallow reservoir exists, both high dip fractures of an E-W strike and low dip fractures were observed. Drilling induced fractures observed in the FMI charts are oriented towards E-W to ENE-WSW directions at a depth interval from 1,505m to 2,650m. This indicates that the stress field, compression approximately in E-W direction, does not change from the surface to the depth of 2,650 m.

TEMPERATURE MEASUREMENTS

Temperature recovery measurements were carried out more than twenty times using a PTS tool, a Kuster tool, and temperature melting tablets composed of metal-based compounds. Several results are shown in Fig. 4 with minimum homogenization temperature of fluid inclusions obtained from cores and cuttings. A temperature profile at a long standing time of Well-18 drilled near WD-1 is also shown. Notice that water circulation was continued up to a depth of 2,500 m during the temperature recovery measurements in order to cool down the borehole and prevent ejection of H_2S gas.

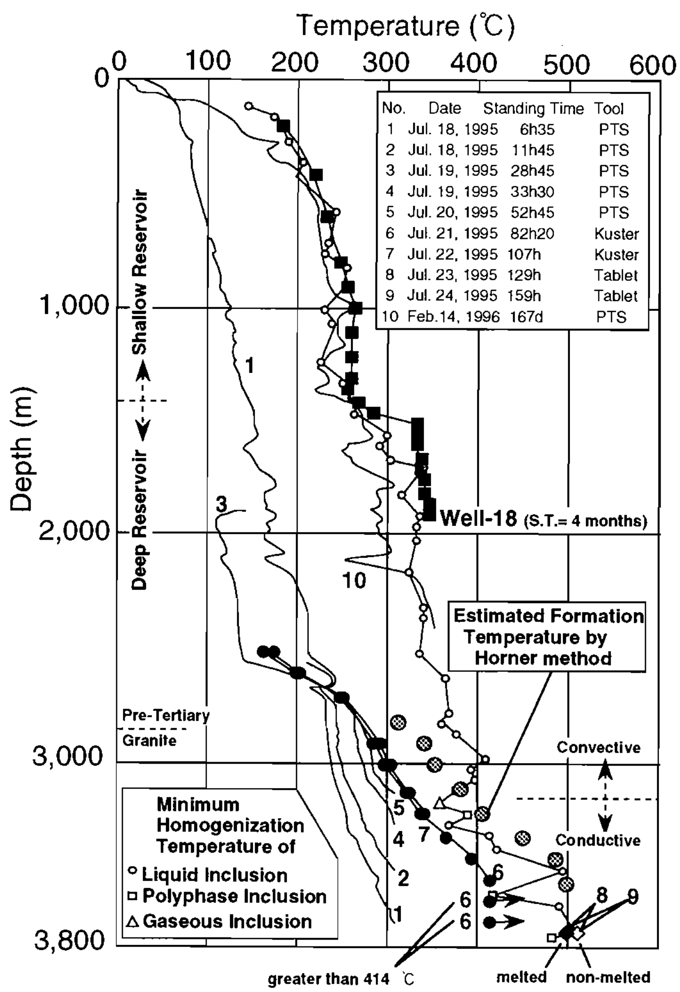

Fig. 4. Several results of temperature recovery measurements and estimated formation temperature by the Horner method. Minimum homogenization temperatures of fluid inclusions from cores and cuttings, and a temperature of Well-18, near WD-1, are also shown.

A recovered temperature of 500 °C, after a standing time of 159 hours, was obtained at the bottom of WD-1a, based on judging whether the tablets were melted or not melted. To verify this observation, a laboratory simulation experiment was later performed by putting the same types of temperature tablets in a condition of 500 °C. The same results of melting and non-melting were obtained, and the temperature of 500 °C was confirmed. This is the highest temperature recorded in a geothermal well in the world.

The temperature estimated by the Horner method was 488 °C at a depth of 3,400 m and 501 °C at a depth of 3,500 m. The temperature profile estimated by the Horner method bends at a depth of approximately 3,200 m. If a temperature profile of Well-18 is extrapolated to the depths greater than 2,000 m, it intersects the estimated temperature profile of WD-1a at a depth of about 3,100 m and does not reach the temperature of 500 °C at the depth of 3,700 m. This indicates the existence of a temperature inflection point at a depth of approximately 3,100 m where the recovered temperature profile drastically changes from hydrothermally convective to thermally conductive. It suggests that the Kakkonda Quaternary granite underlying the reservoirs maintain temperatures above 500 °C and work as a possible heat source of the Kakkonda geothermal system. In addition, we may conclude that there exists a bottom of the hydrothermal convection and meteoric water hardly penetrates under this depth.

CHEMISTRY OF BOREHOLE FLUIDS

We did not encounter any significant fractures during the drilling deeper than 2,500 m. In order to obtain information on deep hyrdothermal fluid, borehole fluids near the bottom of the hole were sampled after the temperature recovery measurements (Kasai at al., 1996). Before the sampling, the borehole fluid was totally replaced by river water. The fluid was then allowed to interact with the granite for 196 hours including the period of the temperature recovery process. Borehole fluids were collected by normal circulation in the depth range from 2,500 m to 3,589 m, while the fluid collection in the depth range from 3,589 m to 3,708 m was performed by reverse circulation, using the drill-strings like a straw, to avoid contamination during the sampling.

The fluids collected near the bottom of WD-1a were extremely high in Cl content to the degree that halite precipitated during the sampling. The estimated salinity of the fluids is approximately 39 wt.%, as a sum of the liquid and solid phases. They were also high in concentration of heavy metals, e.g. 3,400 ppm for zinc and 1,200 ppm for lead. If the pore fluid trapped inside the granite had high salinity, the high salinity of the borehole fluids may be simply attributed to permeation of pore fluid of the granite into the borehole. There is another factor with which the borehole fluids became highly saline. It is the two-phase separation of the fluid in high temperature environment. That is, the fluid in the borehole was separated into low-salinity vapor and high salinity liquid, and the dense saline liquid settled at the bottom. Although the quantitative estimate of the concentration is not available, we may conclude that pore fluid in the granite is abundant both in saline and metallic minerals. Halite-bearing polyphase inclusions with maximum salinity up to 46 wt.% NaCl were observed in quartz sampled from cores and cuttings collected depths over 2,800 m.

Analyses of tritium and δD-$\delta^{18}O$ compositions of the collected fluids and the river water suggest that mixing of the river water and isotopically heavier fluid occurred. It indicates that magmatic fluids may be trapped in fine pores and fractures inside the granite.

Discharge of CO_2 and H_2S gases from the drilling mud was detected by the mud logging during the drilling at depths greater than 3,350 m and 3,642 m, respectively. Each gas was also detected by laser raman spectrometry in fluid inclusions in quartz sampled from cores and cuttings collected at depths over 3,350 m (Ikeuchi et al., 1996).

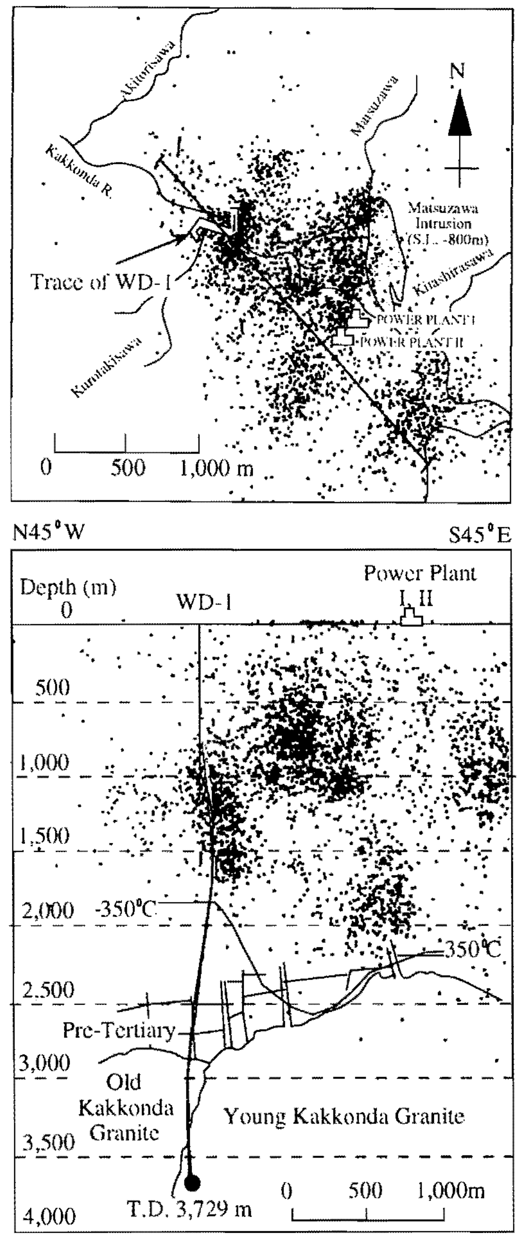

Fig. 5. Distribution of microearthquake hypocenters obtained during a year of 1995; a plan view (top) and a cross section (bottom) along the line shown in the top figure.

MICROEARTHQUAKE MONITORING

Microearthquake activities, mainly associated with fluid circulation and pressure perturbation within the reservoirs, have been monitored by ten seismometer stations since January 1995. Observed microearthquake events are analyzed using computer software named "MEPAS", which was developed by NEDO as a microearthquake analysis system for geothermal exploration (Miyazaki et al., 1993). The estimated velocity structure used for calculation of hypocenter location is one-dimensional (1-D) layered model which was obtained by 1-D inversion of microearthquake data themselves.

The hypocenters form some swarms of NNE-SSW trending along with the major NW-SE trending in this field on a plan view (Fig. 5). On the cross section along the NW-SE direction, we can recognize that the swarms have different depth levels and they are located at depths less than 2,200 m, dominantly in the shallow reservoirs. Microearthquakes were not observed around the top of the granite, and the boundary of this disappearance of the hypocenters coincides with a temperature contour of approximately 350 °C. One of the possible reasons why detectable microearthquakes rarely occur in the deep region is ductility of rocks in high temperature environment, however, we need further investigation to figure out reliable reasons.

SYNTHETIC FLUID INCLUSION LOGGING

A synthetic fluid inclusion logging system has been used experimentally as a temperature logging tool for high-temperature condition over 350 °C, where conventional logging tools are not applicable (Sasada et al., 1996). Gold capsules containing artificially cracked quartz crystals soaked in a silica-saturated alkaline solution were placed in containers, and the containers were hung inside the well, WD-1a. Experiments were carried out at several depths less than 2,500 m under temperatures of up to 350 °C. Fluid inclusions were synthesized in one day under temperatures above 250 °C by using alkaline solution. Homogenization temperatures of the fluid inclusions at each depth were almost coincident with temperature profiles obtained by a conventional logging tool.

ELECTROMAGNETIC SURVEYS

Natural source magnetotelluric method (MT) and controlled-source magnetotelluric method (CSMT) were applied in the Kakkonda field, and subsequent two-dimensional (2-D) inversions were performed. The 2-D resistivity models show the shape of the granite as high resistivity zone. Also, there is another large resistive body in the northwestern side of the field, where WD-1a was targeted and failed to encounter productive fractures.

New tools for borehole electromagnetic surveys, such as multi-frequency and multi-spacing induction logging (MAIL) and frequency-domain surface-to-borehole electromagnetic measurement, are under development in order to obtain detailed structure of the vicinity of WD-1a. This information will be jointly used with the surface magnetotelluric data to improve the reliability of the resistivity model.

GEOTHERMAL MODEL

Summarizing geological, geophysical and geochemical data obtained from the project during fiscal years from 1992 to 1996, the original geothermal model was revised to reflect the location and condition of deep geothermal reservoirs associated with deep and hot granitic intrusions (Fig. 6). Similar intrusions have been discovered in many other geothermal fields, e.g. felsite intrusions in the Geysers (Gunderson, 1992).

The extent of Kakkonda Granite in a plan view is more than 2.0 km x 2.5 km (Doi et al., 1990). The granite has a high temperature and is a possible heat source of the field. The temperature gradient at the depth of over 3,100 m within the granite is approximately 30 °C per 100 m. It is almost ten times as much as the gradient in the depth range from 1,500 m to 3,100 m where a convection system has been developed. The origin of the brine sampled from the granite is considered to be a magmatic residual fluid which came out at the last stage of the magma cooling. Contact metamorphic minerals, such as biotite and cordierite, were observed above the granite. The first appearance of the metamorphic minerals is useful in predicting the depth of the granite during deep drilling.

SIDE-TRACK DRILLING AND FUTURE PLANS

Since WD-1a did not hit productive fractures which we originally expected in the vicinity of the granite, the next step of the project was to drill a side-track well, WD-1b, aiming at a productive fracture near the granite. The side-track drilling was started from a depth of 2,200 m in September 1996. The trajectory of the drilling was decided by examining the data obtained in this project and provided by JMC. WD-1b was deviated southward so that it would cross NE-SW and E-W trending high-dip fractures with higher probability and it would reach a zone beneath a micro-earthquake swarm.

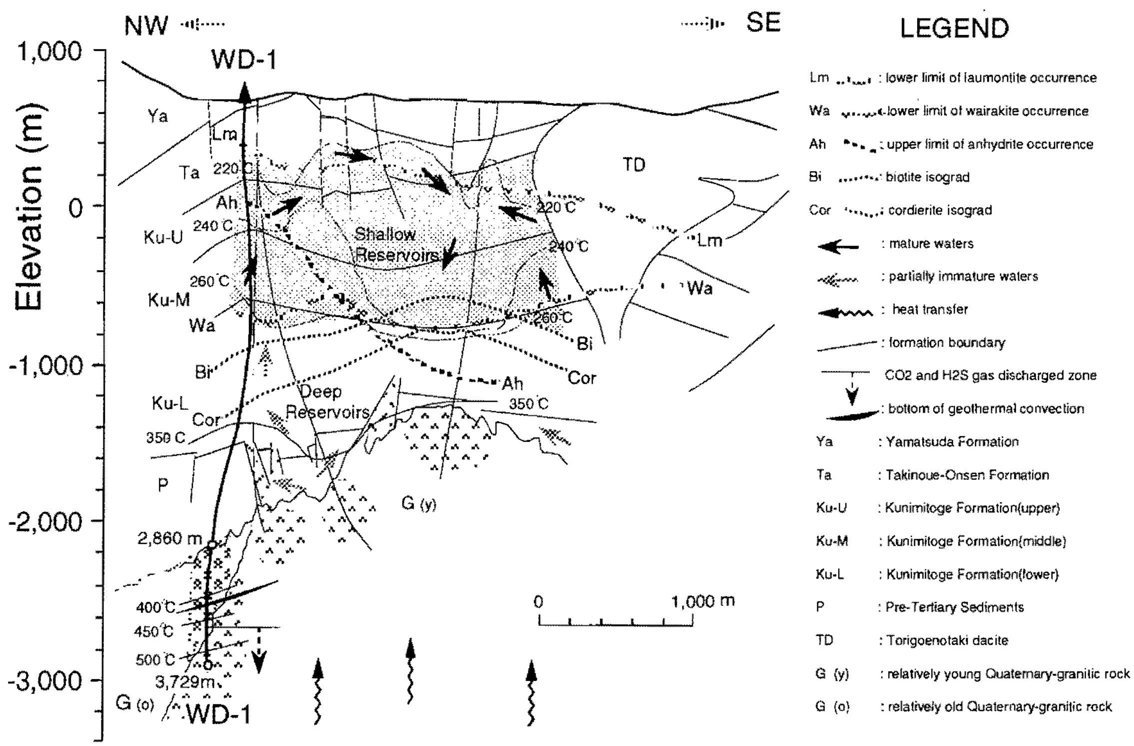

Fig. 6. *A geothermal model on the geologic section associated with the Quaternary granitic intrusion in the Kakkonda geothermal field.*

Formation temperature at the depth of 2,200 m is approximately 350 °C. It is very difficult to use DHM and MWD tools in this kind of high temperature environment. By overcoming several difficulties, we successfully directed WD-1b to the planned trajectory. Total lost circulation occurred at a depth of approximately 2,500 m, however, the drilling was continued with lost-circulation drilling. Finally, the drilling was terminated at a depth of 2,963 m in January, 1997, because of a safety reason against a danger that the drill stem was stuck. Various loggings and other well completion works are now being carried out. A production test of WD-1b, pressure monitoring, experiments of material corrosion, and other associated researches, such as reservoir simulation and resource evaluation, are planned in 1997 and 1998.

CONCLUSIONS

The drilling of WD-1a to a depth of 3,729 m through high-temperature formations yielded much valuable knowledge about deep geothermal systems associated with young and deep intrusions; for example, the thermal structure of the Quaternary granite, the chemistry of fluid within the granite, the distribution of metamorphic minerals, and the fracture systems of shallow and deep reservoirs. The top drive drilling technology supported us to drill into very high-temperature formation of greater than 500 °C. The side-tracked well, WD-1b, recently hit large fractures successfully in the vicinity of the granite. A production test and subsequent reservoir simulation are planned in summer 1997.

However, the characteristics of deep geothermal systems are complicated, and not easy for us to analyze and understand. The distance from the bottom of the deviated well, WD-1b, to the original well, WD-1a, is less than 200 m. One hit large fractures and the other didn't. We have recognized that we should consider the following subjects for development of deep geothermal reservoirs.

- Low permeability in general in the basement and granitic formations
- Generation of fractures in the vicinity and within granitic intrusions
- Ductility in high-temperature environment
- Disappearance of microearthquakes in deep high-temperature reservoirs
- Process of hydrothermal circulation of supersaline fluid in deep reservoirs
- Existence of acid fluid in deep reservoirs
- Emission of H_2S and CO_2 gases from granitic rocks

- Difficulty of exploration for deep reservoirs from the surface in deciding a drilling target

In spite of many successful results reached in this project, achievement of the main purpose of the project, i.e., to establish deep geothermal models and technological guidelines for development, is not an easy task. In addition, the test field of this project has been limited to one geothermal field. Therefore, exchange of research and exploration data of deep geothermal resources, on an international basis, is essential to improve our understanding of the deep resources and to promote further exploitation of deep geothermal energy.

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