

INVESTIGATION OF DEEP GEOTHERMAL SYSTEM IN THE KAKKONDA GEOTHERMAL FIELD, NORTHERN JAPAN

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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 evaluate the possibility of utilizing deep geothermal resources which exist beneath already-developed shallow reservoirs. A deep drillhole, WD-1, has been drilled in the Kakkonda geothermal field located in northern Honshu, Japan. WD-1, which is the deepest geothermal well in Japan, reached a depth of 3,729m in 1995 by applying innovative drilling techniques such as the top-drive drilling system (TDS) and a mud cooling 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. Temperature logging was carried out up to a standing time of 159 hrs using electric temperature tools, a kuster, and temperature melting tablets. We confirmed a temperature greater than 500 °C at the bottom of the well, but we did not encounter major lost-circulations during drilling in the granite. This is the highest temperature recorded in a geothermal well in the world. Borehole fluids near the bottom of WD-1 were collected for geochemical investigation. The Cl content in the fluids was extremely high and the precipitation of halite occurred during the sampling. Side-track drilling of WD-1 is now being conducted from a depth of 2,200 m, targeting productive fractures estimated near the boundary of the granite at a depth of about 3,000 m.

INTRODUCTION

The utilization of deep-seated geothermal resources is expected to significantly increase geothermal power generating capacity in Japan. 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 resources which exist beneath already-developed shallow reservoirs (Uchida et al., 1996).

In this project, NEDO is 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 generation (Figure 1).

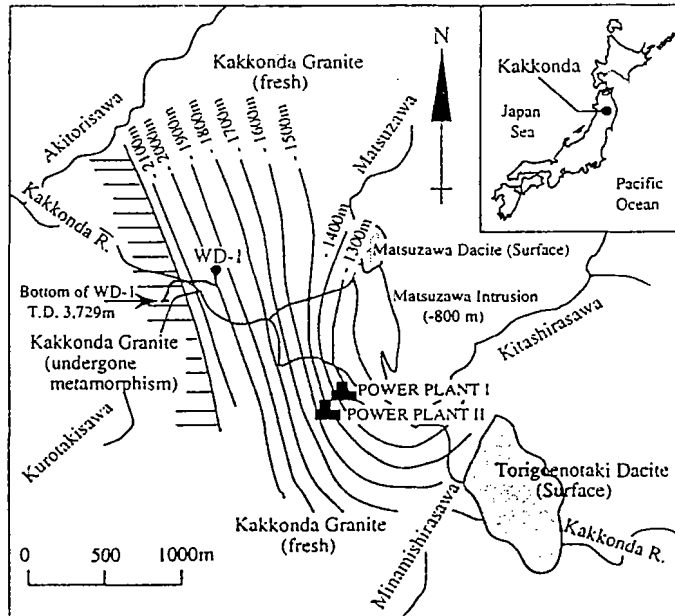


Figure 1. Location of the Kakkonda geothermal field, the trace of WD-1, and contours of the top of the Kakkonda granitic pluton at depths in meters under sea level (modified after Doi et al., 1995).

The three factors essential for understanding geothermal resources, namely, heat supply, hydrothermal fluid circulation, and fracture systems which form reservoirs, have been investigated to establish a geothermal model. The project has four major objectives: to delineate deep and shallow geothermal systems; to develop new exploration methods for deep reservoirs; to systematize deep geothermal drilling; and to examine the possibility of utilizing deep hydrothermal fluids. The final goal of the project is to designate the direction for future development of deep geothermal resources in order to reduce the risk of exploitation and to put deep geothermal energy into practical use.

DRILLING PROGRESS

WD-1 reached a depth of 3,729 m in July 1995. A drilling chart is shown in Figure 2 along with the events which occurred during the drilling.

The top-drive drilling system was applied at depths greater than 1,505 m in order to cool the borehole effectively and reduce the risk of drill-strings getting stuck. A large amount of lost-circulations occurred at a depth range between 1,600 m and 2,150 m, where a shallow reservoir exists. PTS logging was carried out to identify depths of the lost-circulations. Two-stage cementing was successfully carried out to set a 9 5/8" liner-hanger casing to a depth of 2,550 m.

At depths greater than 3,642 m, circulating mud with high H₂S 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-1 reached a depth of 3,729 m with an 8 1/2" hole.

Top-drive drilling coupled with a 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 the borehole can be minimized, and the life of the bits can be extended 10 times longer than when top-drive drilling is not applied.

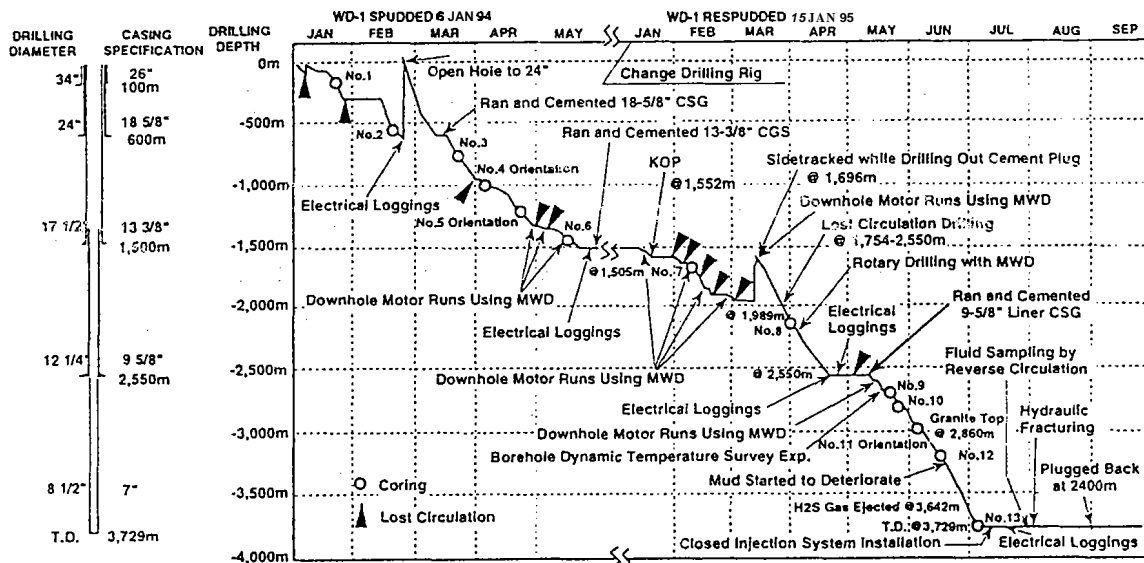


Figure 2. Drilling chart of WD-1.

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-1 is shown in Figure 3.

Geological units observed in the field are, from the surface, Tertiary formations composed of andesite/dacite lapilli tuffs, tuffaceous sandstone and black shale, pre-Tertiary formations composed of andesitic tuffs, shale and sandstone. And, Quaternary granite as well as small andesite/dacite intrusions have been discovered. The boundary between Tertiary and Pre-Tertiary formations is at a depth of

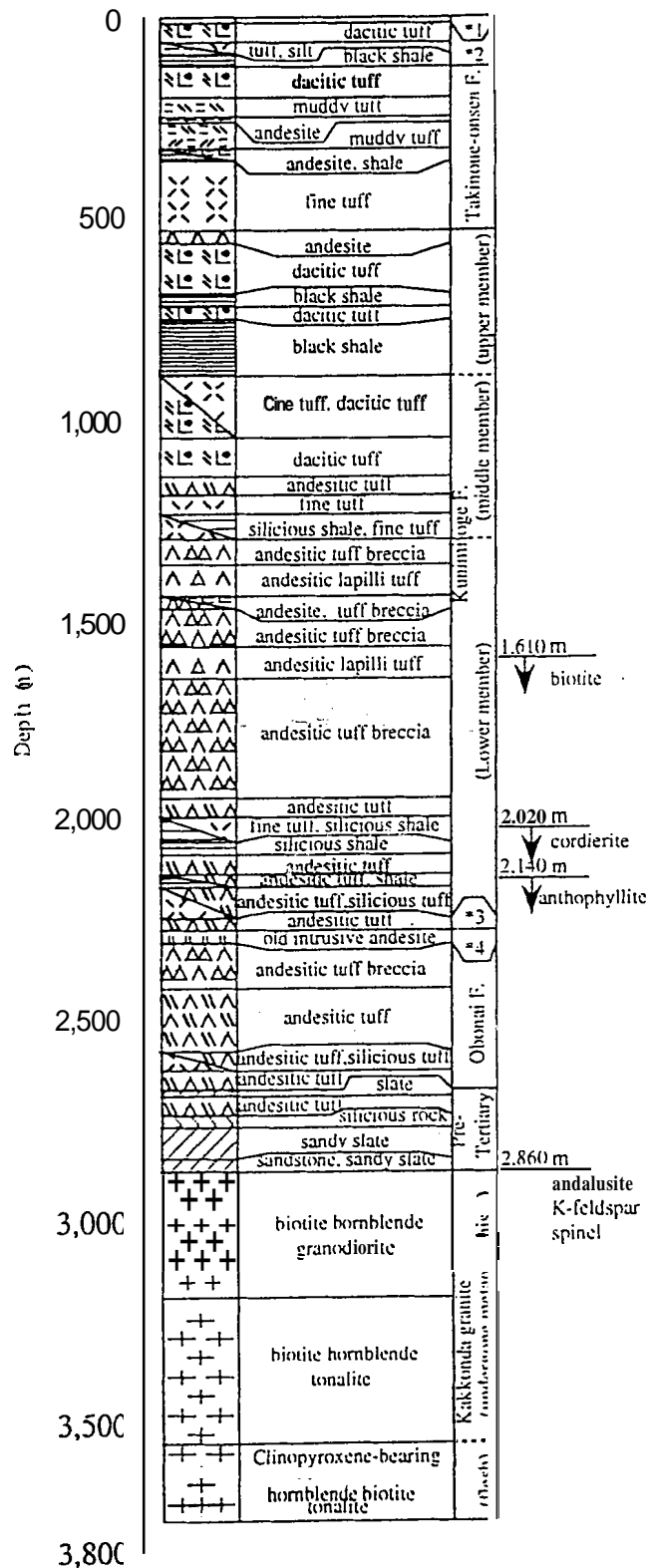
2,660m. Quaternary granite was encountered at a depth of 2,860 m. The first appearance of metamorphic minerals such as biotite, cordierite, anthophyllite and clinopyroxene, which were found at depths of 1,610 m, 2,020m, 2,140 m and 2,860 m, respectively, was helpful in predicting the depth of the granite.

The Quaternary 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 considered 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 $K-Ar$ age of the deepest granite is estimated to be in a range from 0.068 to 0.34 Ma, based on the study by Kanisawa et al. (1994).

BOREHOLE LOGGINGS

Loggings applied in WD-1 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-1, 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 normal resistivity logging.

The FMI logging revealed that drilling-induced fractures 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 a depth of 2,650 m.



*1: detritus, *2: Yamatsuda F., *3: Old Intrusion, *4: Obonai F.

Figure 3. Simplified geological column of **WD-1** and the first disappearance depths of some metamorphic minerals while drilling.

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 Figure 4 along with **minimum** homogenization temperature of fluid inclusions from cores and cuttings. A recovered temperature of 500 °C, after a standing time of 159 hours, was obtained at the bottom of WD-1 based on judging whether the tablets were melted or not melted. The temperature estimated by the Homer method was 501 °C at a depth of 3,500 m, and the extrapolation of the temperature profile estimated by this method downward indicates a formation temperature of 574 °C at a depth of 3,700 m (Ikeuchi et al., 1996). The Kakkonda Quaternary granite underlying the reservoirs maintain temperatures above 500 °C and are considered to be a possible heat source of the Kakkonda geothermal system.

The temperature profile estimated by the Horner method bends at a depth of approximately 3,100 m. If a temperature profile of Well-It, which was drilled near WD-1, is extrapolated to the depths greater than 2,000 m, it intersects the profile of WD-1 estimated by the Homer method 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 there is a bottom to the hydrothermal convection, which means that meteoric water hardly penetrates below this depth.

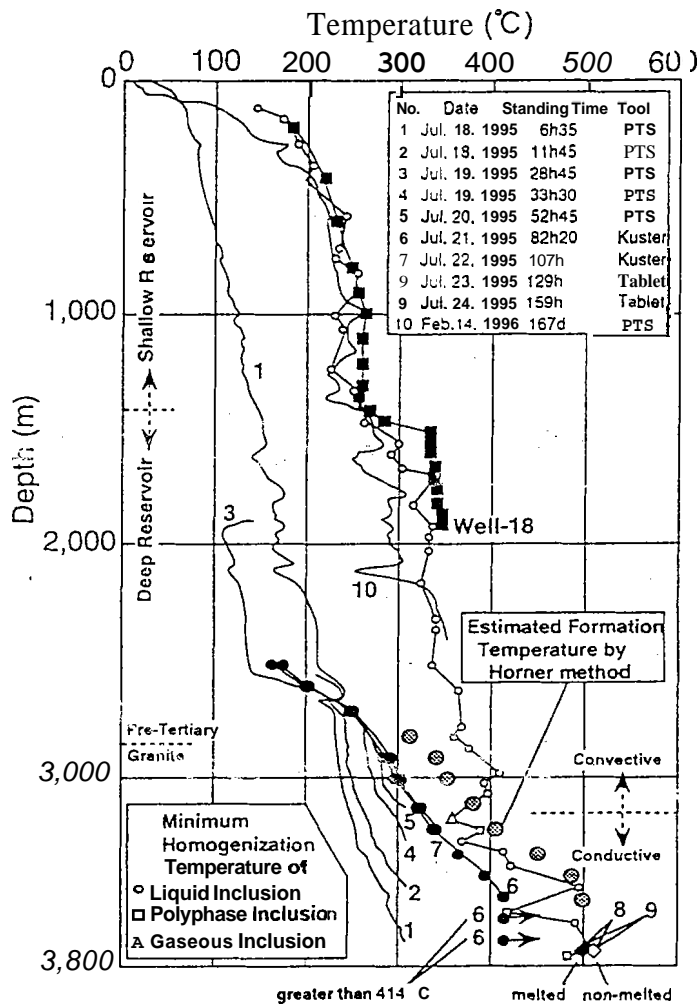


Figure 4. Some results of temperature recovery measurements.

CHEMISTRY OF BOREHOLE FLUIDS

Fluids from the WD-1 borehole were sampled after the temperature recovery measurements. Before the sampling, the borehole fluid was completely replaced by river water supplemented with $\text{Ca}(\text{OH})_2$ to avoid the discharge of H_2S gas. The fluid was then allowed to react with the granite for 196 hours under the extremely high temperature in the borehole (more than 500 °C) before it was collected. Fluids were collected by normal circulation in the depth range from 2,500 m to 3,589 m. To avoid contamination during the sampling, 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,

The fluids from the bottom of WD-1 turned out to be extremely high in Cl content, above ~~22~~³⁹ wt%, with a high concentration of heavy metals such as iron, manganese, zinc, and lead. Possible explanations

for the origin and the mechanism of the concentration of Cl sampled from the bottom of WD-1, as well as extracted gases while drilling in the granite, are discussed from the following points: shifts of oxygen and hydrogen isotope ratios (e.g., Kasai et al., 1996), change of ~~tritium~~ concentration, and the geothermometry of natural fluid inclusions. CO₂ and H₂S gases were detected by laser raman spectrometry within two-phase fluid inclusions trapped in a quartz vein at the bottom of the WD-1 core.

MICRO-EARTHQUAKE MONITORING

Micro-earthquake hypocenters have been observed by ten seismometer stations since January 1995. The data acquired has been analyzed using computer software named "MEPAS", which was developed by NEDO as a micro-earthquake analysis system for geothermal exploration (Miyazaki et al., 1993). Concentration of the hypocenters forms NW - SE trending from a plane view and extends deeper toward the west on the cross-section. This indicates that fractures continue to a deeper subsurface along the well trace of WD-1 located in the western part of the Kakkonda geothermal field. However, only a few hypocenters are observed approximately at a depth of over 2,200 m from the surface in the whole area of Kakkonda. The boundary for disappearance of hypocenters coincides with the temperature contour of 350 °C.

ELECTROMAGNETIC SURVEYS

Natural source magnetotelluric method (MT) and controlled-source magnetotelluric method (CSMT) were applied in the Kakkonda field, and subsequent two-dimensional inversion was performed. New tools for borehole electromagnetic surveys, such as Multi-frequency Array Induction Logging (MAIL) and Vertical Electro-Magnetic Profiling (VEMP), are under development to obtain detailed structure of the vicinity of WD-1. This information will be jointly used to improve the reliability of the resistivity model.

GEOHERMAL 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 predict the extension of deep geothermal reservoirs. The model is being used to examine the location and conditions of deep geothermal reservoirs associated with a deep and hot intrusion, which has been found in many geothermal fields, such as the felsite intrusion in The Geysers (Gunderson, 1992).

The extension of the Quaternary granite in a plane 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 between the depth range from 1,500 m to 3,100 m, where a convectional system exists. The origin of the brine sampled from the granite is considered to be a magmatic residual fluid emitted at the last stage of the magma cooling. Contact metamorphic minerals, such as biotite and cordierite, were observed over the granite. The first appearance of the metamorphic minerals is useful in predicting the depth of the granite during deep drilling.

FUTURE SCHEDULE

The accomplishment of drilling to 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 fracture system of shallow and deep reservoirs, and the distribution of metamorphic minerals.

Since September 1996, side-track drilling has been conducted in order to investigate fluid flow in the system and consequently evaluate the potential of deep geothermal resources. It targets productive fractures expected to be around a depth of 3,000 m. Also, a flow test and associating measurements are planned after a large, deep reservoir is hit by drilling.

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