Information on the Kakkonda Deep Geothermal Reservoir Obtained by Side-track Drilling of WD-1

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ABSTRACT

NEDO has been conducting a research project titled "Deep-Seated Geothermal Resources Survey" since 1992. Drilling of a deep drillhole, WD-1a, reached a depth of 3,729 m in July 1995. However, WD-1a did not encounter large lost circulation near the boundary of Quaternary granite. In order to hit deep reservoirs which are expected to exist near the boundary of the granite, side-track well, WD-1b, was drilled. WD-1b encountered large lost circulations near the boundary of the granite. Side-track drilling was terminated at a depth of 2,963 m in January 1997.

Introduction

The utilization of deep geothermal resources is integral to maintaining and increasing the power generating capacity of already-developed geothermal fields. NEDO has been conducting a research project titled "Deep-Seated Geothermal Resources Survey" since 1992 under the New Sunshine Project of the Ministry of International Trade and Industry (MITI). It aims to investigate the characteristics of deep geothermal systems and evaluate the possibility of utilizing deep geothermal fluids which exist beneath already-developed shallow reservoirs (Uchida et al., 1996). As a part of this project, NEDO has drilled 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 totaling 80 MWe (Figure 1).

The 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 both deep and shallow structures. The project has four major objectives: to delineate deep and shallow geothermal systems; to develop new exploration tools for deep reservoirs; to evaluate current drilling technologies for deep geothermal drilling; and to examine materials applicable for production of deep hydrothermal fluids by conducting corrosion and erosion tests. The final goal of the project is to establish recommended technological guidelines for future development of deep geothermal resources in order to reduce risk of exploitation and to put deep geothermal energy into practical use.

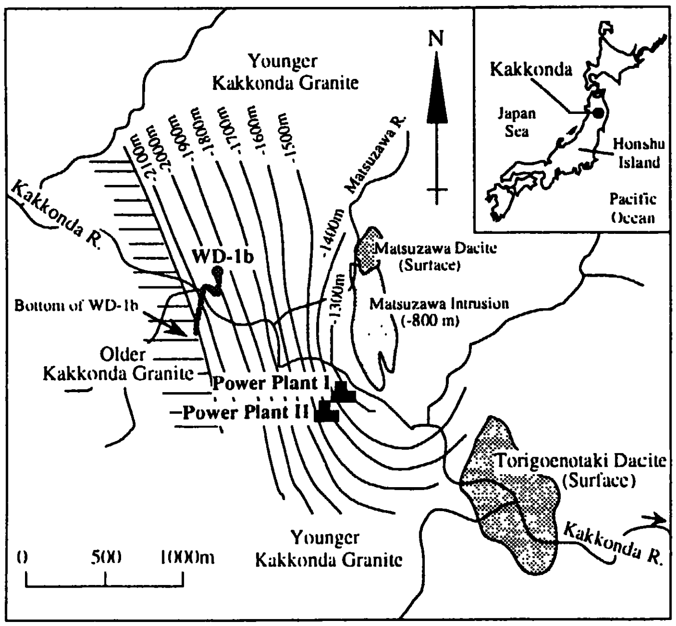

Figure 1. Location of the Kakkonda geothermal field, the trace of WD-1b, and contours of the top of the Kakkonda granitic pluton at depths in meters below sea level (modified from Doi et al., 1995).

Drilling of WD-1 has been carried out in two stages. In the first stage, drilling of the main well, WD-1a, which reached a depth of 3,729 m in July 1995, was carried out by applying the latest drilling techniques including the top-drive drilling system (TDS). This enabled both successful drilling in a very high temperature formation and the collection of valuable information for understanding the characteristics of deep geothermal systems. In the second stage, a side-track well, well, WD-1b, was drilled from a depth of about 2,200 m down to 3,000 m. Field operations for second stage drilling was started in September 1996, targeting productive fractures expected to exist near the boundary of the granite at depths ranging from 2,800 m to 3,000 m.

Results of WD-1a

A deep drillhole, WD-1a, was drilled in the Kakkonda geothermal field from January 1994 to July 1995. A large amount of lost circulations occurred at depths ranging from 1,600 m to 2,150 m, where a shallow reservoir is known to exist. However, WD-1a did not encounter large lost circulation near the boundary of Quaternary granite. WD-1a was drilled into the granite for a length of 870 m to determine the thermal structure and deep fracture systems. Finally WD-1a reached a depth of 3,729 m. After various loggings were carried out, WD-1a was plugged back to a depth of 2,400 m.

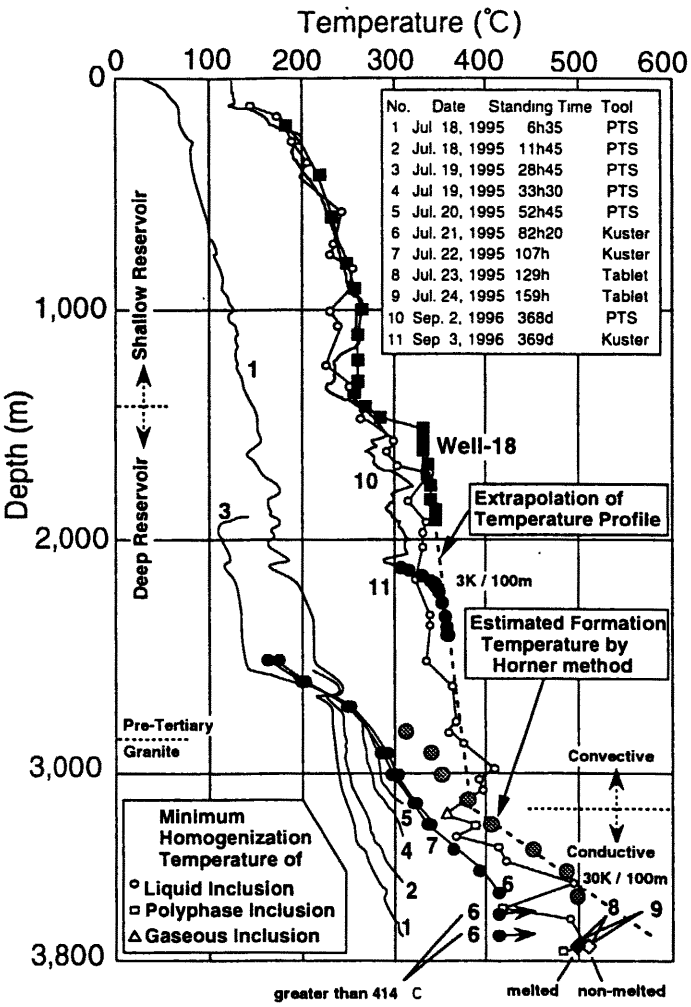

Figure 2. Several results of temperature recovery measurements and estimated formation temperature by the Horner method. Minimum homogenization temperatures of fluid inclusions from cores and cuttings, and a temperature profile of Well-18, near WD-1, are also shown.

TDS and a mud cooling system were applied in order to cool the borehole effectively and reduce the risk of drill-string getting stuck. Also, trajectory correction runs using a downhole motor (DHM) tool were applied under high-temperature conditions. This was enabled by the use of TDS.

Drilling through high-temperature formations yielded much valuable knowledge about deep geothermal systems associated with young intrusions, including knowledge on such subjects as the thermal structure of Quaternary granite, the chemistry of the fluid within the granite, the distribution of metamorphic minerals, and the fracture systems of shallow and deep reservoirs.

Several results of the temperature recovery measurements are shown in Figure 2 with the minimum homogenization temperature of fluid inclusions obtained from from cores and cuttings. A long standing time temperature profile of Well-18, drilled near WD-1a, is also shown. A recovered temperature of over 500°C, after a standing time of 159 hours, was obtained at the bottom of WD-1a by using temperature melting tablets (Ikeuchi et al., 1996). The static formation temperature gradient of WD-1a estimated by the Horner method was $3.2x10^{-1}$ K/m at depths between 3,200 m and 3,500 m. On the other hand, the temperature gradient of WD-1a at depths between 1,500 m and 2,000 m was $3.2x10^{-2}$ K/m, which is similar to that of Well-18. If the temperature profile of Well-18 is extrapolated to depths greater than 2,000 m, a temperature inflection point is recognized at a depth of approximately 3,100 m. The recovered temperature profile drastically changes from hydrothermally convective to thermally conductive at this depth. This indicates that the Kakkonda Quaternary granite underlying the reservoirs maintains temperatures above 500°C and works as a possible heat source of the Kakkonda geothermal system. In addition, it may be said that there exists a bottom to the hydrothermal convection and meteoric water hardly penetrates below this depth.

The distribution of micro-earthquake hypo-centers forms swarms which are NE-SW trending from a plane view and extend deeper toward the west on the cross-section (Figure 3). The trace of WD-1a went outside of the swarms on a plane view and did not encounter any productive fractures. It can be inferred that many fractures exist under swarms of micro-earthquake hypocenters on the plane view in the Kakkonda field. According to fracture analyses of the Formation Micro Imager (FMI; trademark of Schlumberger) logging data, the stress field, which is compressive approximately in an E-W direction, does not change from the surface to a depth of 2,650 m (Kato et al., 1995).

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 a 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.

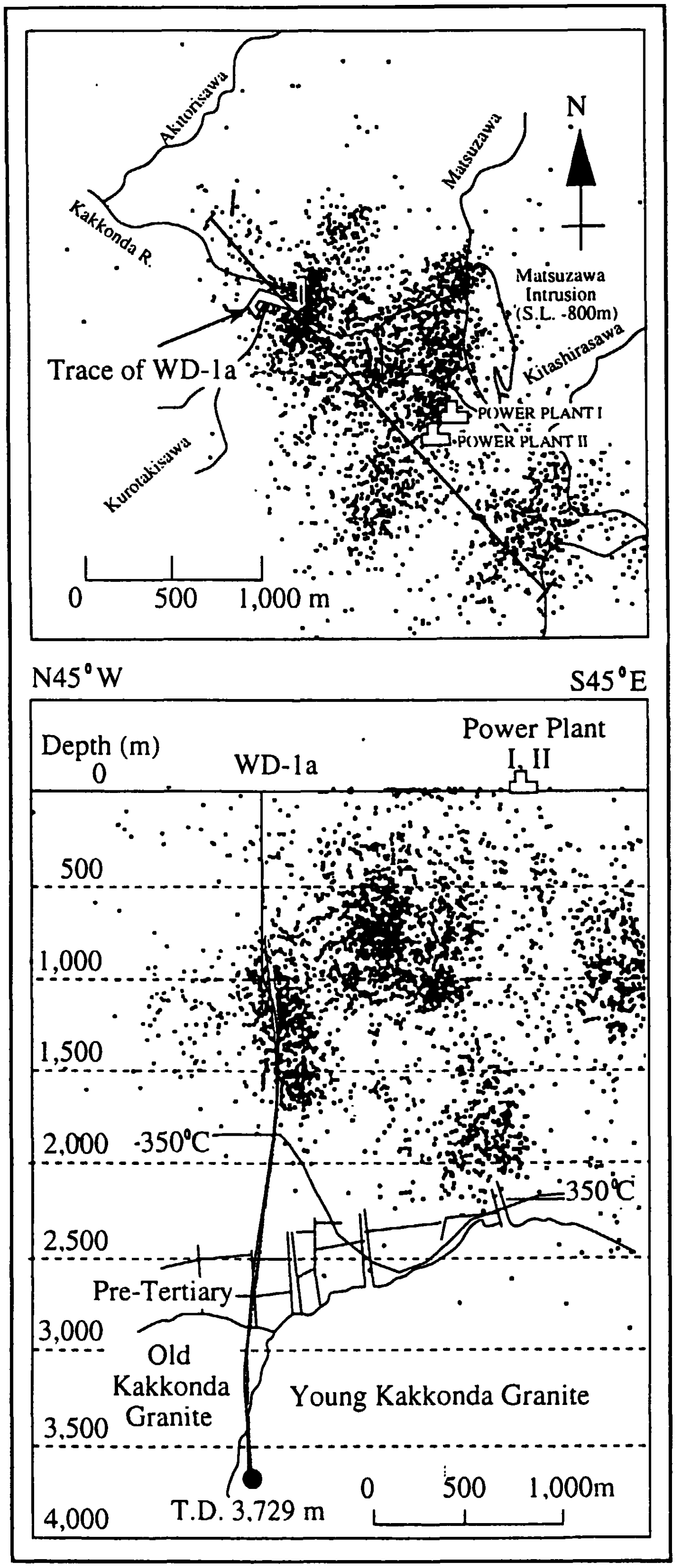

Figure 3. Distribution of micro-earthquake hypo-centers obtained during fiscal year 1995; a plane view (top) and a cross section (bottom) along the line shown in the top figure.

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. fluid emitted 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 metamorphic minerals is useful in predicting the depth of the granite during deep drilling.

Summarizing geological, geophysical and geochemical data obtained in the project from fiscal year 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 (Figure 4).

Establishment of the Target for WD-1b

In order to hit deep reservoirs which are expected to exist near the boundary between Pre-Tertiary formations and the Quaternary granite, side-track drilling to a depth of 3,000 m was planned. By examining the data obtained by the drilling and various surveys of WD-1a, it was decided to deviate the side-track well, WD-1b, southward from the original well, WD-1a (Figure 5). To avoid a large amount of lost circulations at depths above 2,150 m, side-track drilling of WD-1b was planned from a depth of about 2,300 m circulations at depths above 2,150 m, side-track drilling of WD-1b was planned from a depth of about 2,300 m.

Drilling of WD-1b

A drilling chart of WD-1b is shown in Figure 6 along with the events which occurred during the drilling. The side-track drilling of WD-1b was started at a depth of 2,300 m in September 1996. The whipstock was set in a 9 5/8" casing and milling was carried out. Then trajectory correction was tried using DHM. However, the first side-track drilling failed to change direction and the trajectory went along WD-1a.

The second side-track drilling was started at a depth of 2,194 m. The whipstock was set in a 9 5/8" casing and milling was carried out again. During the trajectory correction by using DHM, Gyro measurements were applied three times in order to measure the exact trajectory. The second side-track drilling successfully deviated to the planned direction. A little lost circulation started when the drilling was reached a depth of 2,478 m. Although spot-cementing was applied several times to stop the lost circulation, it grew larger and became total lost circulation. Therefore, lost circulation drilling was applied at a depth of 2,488 m. WD-1b encountered some productive fractures near the boundary of the granite, including a 40 cm drilling break at a depth of 2,816 m. A core sample was collected at a depth of 2,820 m and Pre-Tertiary formation was confirmed at this depth. WD-1b hit the boundary of the granitic formation at a depth of about 2,839 m. The side-track drilling was terminated at a depth of 2,963 m with with an 8 1/2" hole in January 1997.

Formation temperature at a 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 conditions. By overcoming several difficulties, WD-1b was successfully directed to the planned trajectory.

Just before setting the 7" strainer, the drill string was stuck near the bottom of the drillhole, probably due to the collapse of the drillhole wall. The drill pipe was finally backed off at a depth of 2,633 m and the string below this depth was left there.

Loggings in WD-1B

Loggings applied in WD-1b are as follows: temperature logging, normal resistivity logging, TS logging, *UltraSonic Imager (USI), *FMI, *Dual Latero-Log, *Dipole Shear-Sonic Imager, *Litho Density Logging and natural gamma-ray logging (*trademark of Schlumberger). These loggings were performed down to the bottom of the well before the drill string was stuck.

New tools for borehole electromagnetic surveys, such as the Multi-frequency Array Induction Logging (MAIL) method and the Vertical ElectroMagnetic Profiling (VEMP) method, are now being developed and tested in WD-1b in order to obtain detailed structure of the vicinity of the well. This information will be jointly used with the surface magnetotelluric data to improve the reliability of the resistivity model.

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. Top drive drilling technology supported the drilling into formations of temperatures higher than 500°C.

The side-track well, WD-1b, encountered fractures near the boundary of the granite and various loggings were carried out. A production test of WD-1b, pressure monitoring, experiments of material corrosion, and other associated research, such as reservoir simulation and resource evaluation are planned for 1997 and 1998.

The distance from the bottom of the deviated well, WD-1b, to the original well, WD-1a, is less than 200 m. One well hit large fractures and the other didn't. This indicates the complexity of deep geothermal systems. It has been recognized that the

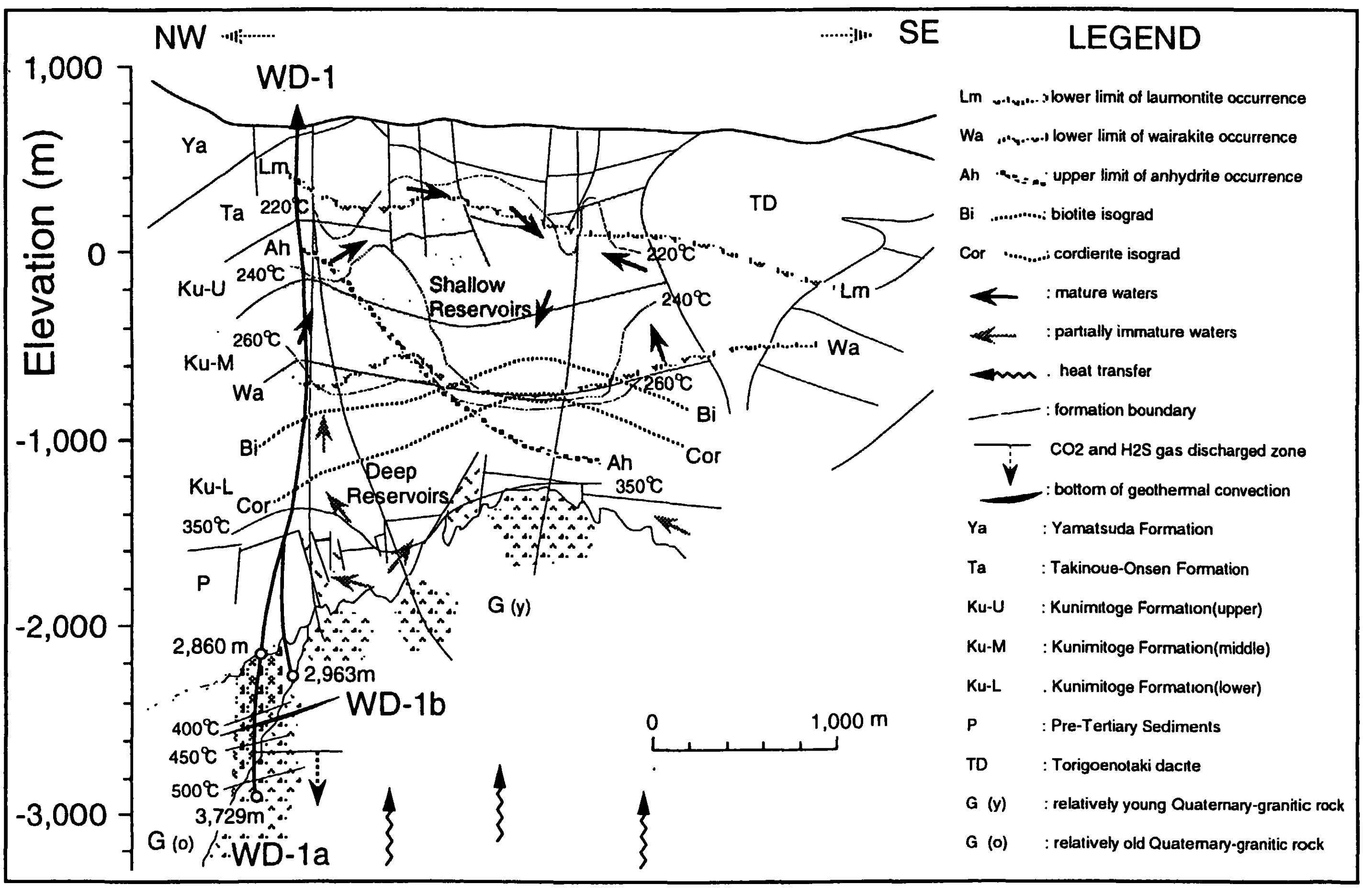

Figure 4. A geothermal model on the geologic section associated with the Quaternary granitic intrusion in the Kakkonda geothermal field.

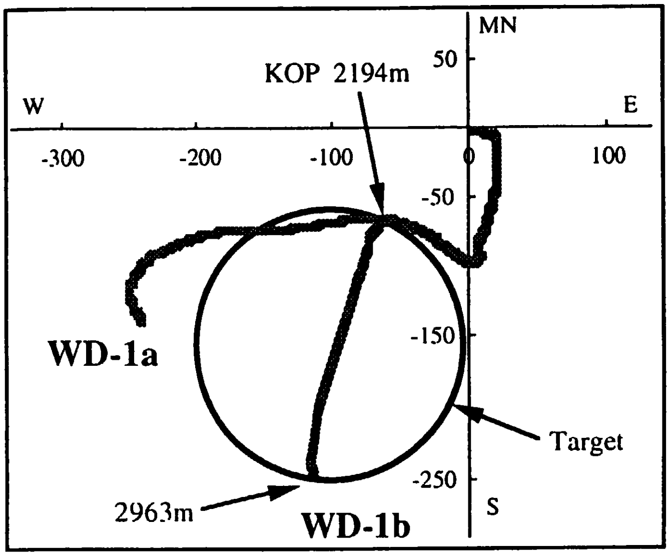

Figure 5. Trajectories of WD-1a and WD-1b on a plane view. The circle is the target of WD-1b. The target depth was 2835 m, where WD-1b was expected to encounter the boundary of Quaternary granite.

following subjects should be considered for the development of deep geothermal reservoirs.

- Generally low permeability in the basement and granitic formations
- Generation of fractures in the vicinity of and within granitic intrusions
- Ductility in high-temperature environment
- Disappearance of microearthquakes in deep high-temperature reservoirs
- Process of circulation of meteoric water fluid in deep geothermal system
- Existence of acid and/or supersaline fluid in deep geothermal system
- Emission of H2S and CO2 gases from granitic rocks
- Difficulty of exploring deep reservoirs from the surface in deciding a drilling target

The many successful results have been achieved in this project, and the main objective of the project, i.e., to establish deep geothermal models and technological guidelines for development, is examining. For that purpose, exchange of research and exploration data regarding deep geothermal resources on an international basis is essential for improving our understanding of the deep resources and to further promote exploitation of deep geothermal energy.

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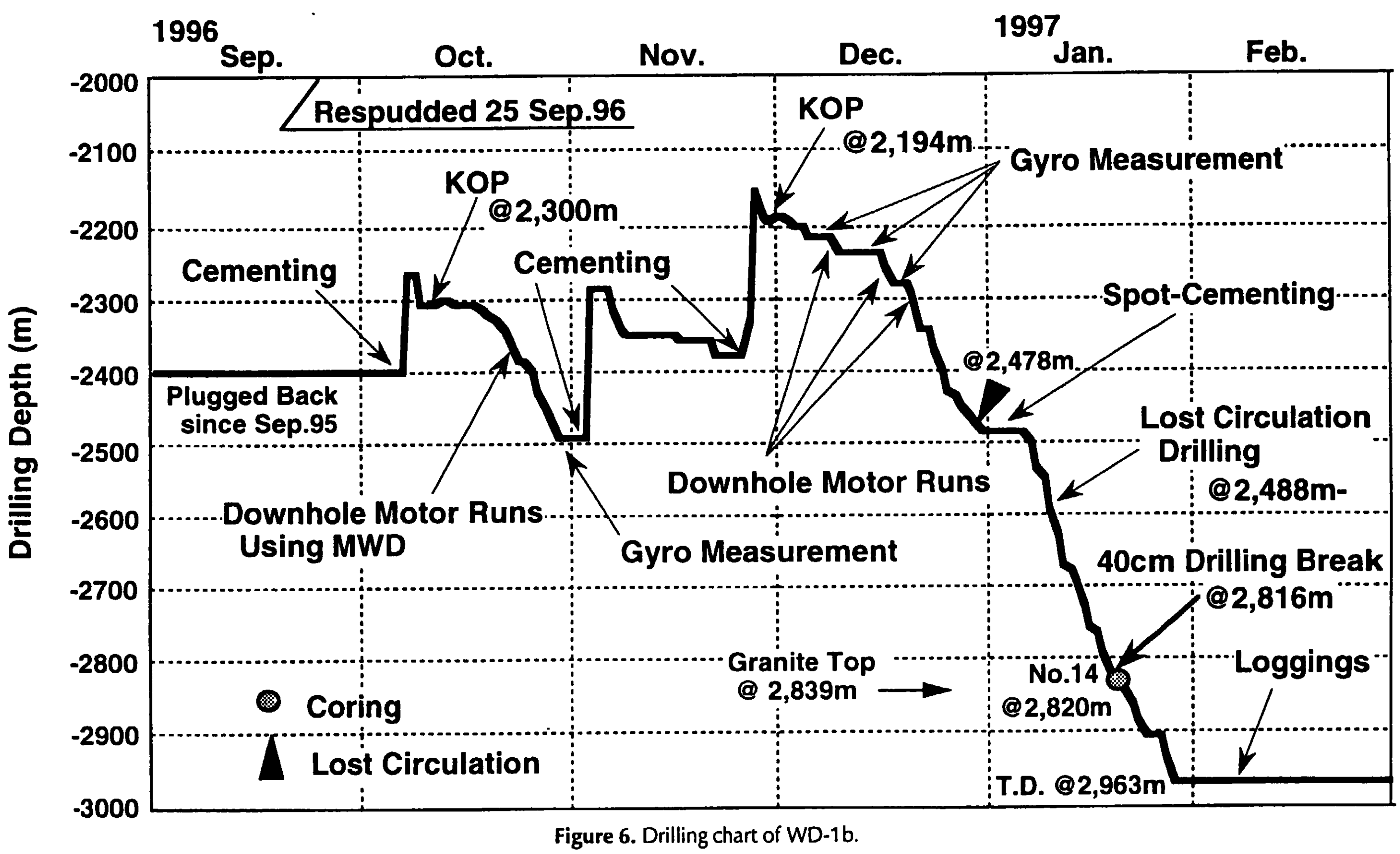

Figure 6. Drilling chart of WD-1b.

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