New Geophysical Exploration Methods in NEDO "Deep-seated Geothermal Resources Survey"

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Kakkonda geothermal field, micro-earthquake activities, Vertical Electromagnetic Profiling (VEMP), Multi-frequency Array Induction Logging (MAIL)

ABSTRACT

NEDO began the research project "Deep-seated Geothermal Resources Survey" in FY-1993[1]. A drillhole, WD-I, which will be the deepest (4,000 m class) and hottest (over 350℃) well in Japan, is being drilled at the Kakkonda geothermal field.

In this research project a variety of new geophysical exploration methods are scheduled in addition to conventional ones. Multi-frequency array induction logging and vertical electro-magnetic profiling surveys have been done during intervals in the drilling. To interpret the data, software for a joint analysis of these new electromagnetic methods and the CSMT method will be developed. A longterm micro-earthquake activity survey will be conducted to monitor the fluid flow in the fracture systems. The data from this survey will be analyzed using seismic wave speeds calculated from VSP data. The conceptual bases for a combined analysis of new and ordinary survey methods are introduced in this paper.

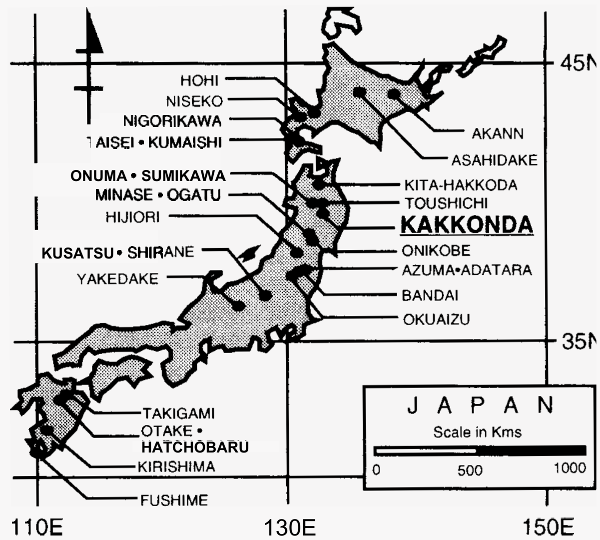

Figure 1 Prospected areas of deep-seated geothermal resources in Japan

INTRODUCTION

In order to increase geothermal power generation in Japan, NEDO started a six-year project "Deep-seated Geothermal Resources Survey" (Sasada et al., 1993) in FY-1992 as a part of the New Sunshine Project of the Ministry of International Trade and Industry (MITI). The purposes of the survey are to delineate deep-seated geothermal resources, to investigate the entire geothermal environment including shallow systems, and to evaluate the possibility of utilizing deep hydrothermal fluids. The final goal of the project is to designate directions for the development of deep geothermal resources to reduce the risk of deep exploitation and to put deep geothermal energy into practical use.

For this survey, the Kakkonda geothermal field, where a shallower reservoir system had already been investigated, was selected (Figure 1) and a drillhole which will be the deepest (4,000 m) and hottest one in Japan (over 350 to 400°C) began to be drilled in the beginning of 1994. In Kakkonda, a 50 MWe power plant has been in operation since 1978, and a second power plant (30 MWe) is scheduled to begin operation in 1996. Tohoku Electric Power Inc. (TEP) is the operator of both of them and Japan Metals and Chemicals Co., Ltd. (JMC) and Tohoku Geothermal Energy Co., Ltd. (TGE) are the steam suppliers. JMC recently identified the existence of a neo-granitic pluton and its related potential reservoir by drilling two deep drillholes 2.5 - 3.0 km in the Kakkonda area (Doi et al., 1990).

The 4,000 m drillhole is called Wedge-I (WD-I). This stands for "Well for Deep Geothermal Evaluation." The drilling process of WD-I includes mud logging, cutting and core surveys. Various kinds of electrical logging, including formation micro-imager (FMI), are conducted during intervals in the drilling. Several new investigation methods for deep geothermal reservoirs, such as micro-earthquake activity monitoring, synthetic fluid inclusion surveys, and vertical electromagnetic profiling (VEMP) surveys, are also planned.

Currently WD-I has reached a depth of 1,505 m with 13 3/8" diameter casings. The top-drive drilling system will be applied for depths over 1,505 m where recovery temperature is over 260%. The top-drive drilling system enables continuous mud pumping and it cools the drillhole effectively. It also allows the use of the measurement - while - drilling (MWD) system, by which the drilling direction can be monitored. By introducing these new systems the efficiency of these methods for deep geothermal drilling will be evaluated throughout the project.

For the following years, in addition to those surveys discussed above, flow tests are scheduled at two different depths (about 2,950 m and 4,000 m) when the drillhole hits the deep reservoirs. Temperature and pressure monitoring surveys, tracer tests, and casing corrosion and erosion tests will be conducted during the flow tests.

[1] Fiscal year in Japan begins on April 1st and ends on March 31st

GEOLOGICAL FEATURES AND A GEOTHERMAL MODEL OF THE KAKKONDA GEOTHERMAL FIELD

Geological features of the Kakkonda geothermal field have already been described in detail by several authors, including Nakamura and Sumi (1981), Sato (1982), Doi et al. (1990), Kato et al. (1993), and Hanano and Takanohashi (1993). A description of the neo-granitic rock has been given by Kato and Doi (1993), and its age is estimated to be 0.34 - 0.14 Ma by the K-Ar method with a mineral separation (Doi et al., 1993). Fracture analysis and characterization **of** the surface vein in the Kakkonda field was done by Koshiya et al., in 1993 and 1994. Geological aspects of the recent results from WD-I are reported in Yagi et al. (1994).

Analyzing existing geological and geophysical data, the extension of the deep geothermal reservoirs were estimated (Figure 2) in the first phase of the geothermal model. The model represents deep-seated geothermal resources associated with a deep and hot intrusion, a phenomena which has been found in many geothermal exploration fields such as the felsite body in The Geysers (e.g. Gunderson, 1992).

The extension of the neo-granitic pluton is over 2.0 x 2.5 km (Doi et al., 1993). The present temperature of the neo-granitic rock is greater than *350°C.* Contact metamorphic minerals, such as cordierite and biotite, were observed above the top of the neo-granitic rock. The upper limit of the biotite-cordierite zone exists at 600 - 700 m above the contact of the neo-granitic rock, while the upper limit of the biotite zone is at 700-1,000 m (Kato and Doi, 1993). Therefore, the first appearance of these metamorphic minerals must be a good indicator of the top of the neo-granitic rock (see Figure 2). According to the results of the cuttings investigation for the interval of 0 to 1,505m, biotite has not yet been detected. This suggests that the top of the neo-granitic rock may descend toward the west.

Lost circulation of mud has been observed at depths of 42 m, 273 - 280 m, 980 m, 1,291 m, 1,327 m, and 1,345 m.

ELECTRIC AND MAGNETIC SURVEY METHODS

Exploration of deep-seated geothermal reservoirs is significantly more difficult compared to that of shallow ones because of their vertical location. Being one of the more effective exploration methods, the magnetotelluric (MT) method is widely used to ascertain resistivity structures in order to assess deep geothermal systems. However, the resolution of the MT method drastically decreases with depth. On the other hand, electric and/or magnetic surveys using drillholes have a higher resolution for deeper sections but spatially cover only a narrow range. By conducting a joint analysis of experiments at the surface and in the drillhole, higher resolution, accuracy, and coverage can be achieved (See Figure 3).

In the "Deep-seated Geothermal Resources Survey", combined analysis of three electro-magnetic survey methods will be camed out as follows:

(1) Multi-frequency Array Induction Logging, which has high resolution around the well but low spatial coverage.
(2) Vertical Electromagnetic Profiling Survey, which has intermediate resolution and covers the triangular area between the surface and the borehole.
(3) Magnetotelluric method, which covers horizontally and vertically a large area but has low resolution for deeper sections.

The first two methods have only recently been developed and will be improved in this project. For each of the three methods, data from the other two methods will be used as constraining conditions which will result in a higher resolution of the inverted resistivity distribution.

Multi-frequency Array Induction Logging

Multi-frequency Array Induction Logging (MAIL) is an induction log which has multiple receivers and a variable frequency source MAIL has the following advantages compared to a regular induction log

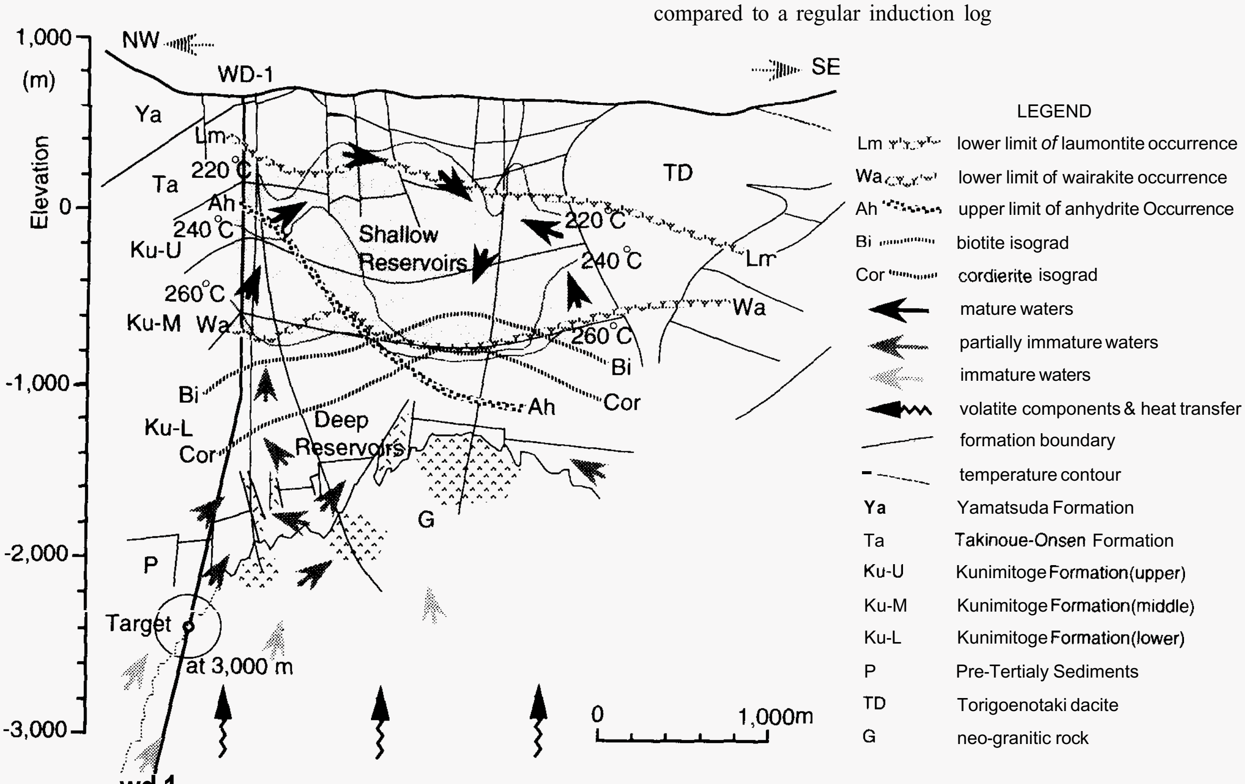

Figure 2. Prospected geological section in the Kakkonda geothermal field.

(1) By applying a highly sensitive induction coil in the receiver the accuracy of observation will be raised.
(2) By applying a multi-frequency source in combination with multiple coils, information about the formation will be acquired more precisely.
(3) The image of the resistivity distribution around the borehole will be calculated by model inversion analysis using amplitude and phase data.

In May, 1994, MAIL survey was carried out in WD-I at depths from 605 m to 1,500 m. The data will be calibrated by temperature and analyzed by inversion programs.

Vertical ElectroMagnetic Profiling Survey

The vertical electromagnetic profiling (VEMP) method is a way to obtain multi-frequency three-component magnetic field data in a drillhole using controlled sources on the surface (Figure 4). A receiver in the borehole (three component magnetic field sensors) and surface receivers (EM receivers) and surface sources (grounded wire and loop sources) are used. This survey covers the triangular range shown in Figure 3.

A VEMP survey was carried out in WD-I for depths between 605 m and 1,500 m for a frequency of 11 Hertz. Numerical simulations of the VEMP survey had been made in advance to determine an adequate magnitude and frequency range of the sources. This field data will be analyzed both by VEMP data only and by combination with CSMT data. A software for the joint analysis will be developed in FY-1995.

Controlled Source Magnetotelluric Survey

An array-type controlled source magnetotelluric (CSMT) survey was conducted in Kakkonda at the end of July, 1994. The receiver amy covered a surface range longer than 6.1 km and contained over sixty observation points. The CSMT data will be used for a joint analysis with the VEMP data to get a more precise resistivity structure of the Kakkonda geothermal system.

The CSMT source, which is 2.8 km long and is parallel to the receiver array, was located 8 km from the receivers. The frequency range of the source is 1 to 4,000 Hertz. For the low frequency range, an MT survey was also conducted at the same observation points. This data will be analyzed two-dimensionally.

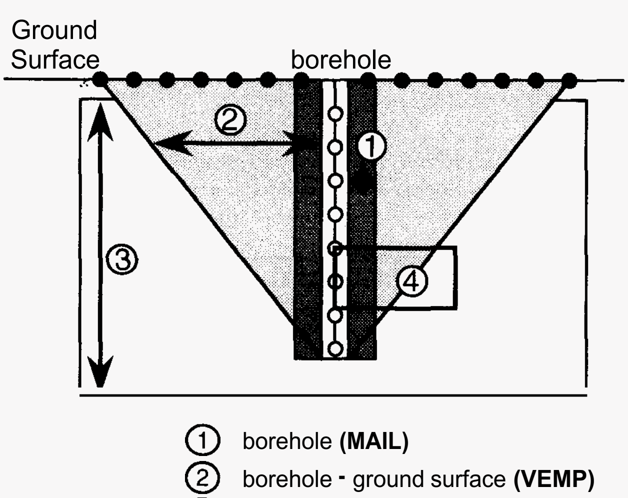

Figure 3. Schematic model of the combined analysis of three electromagnetic surveys.

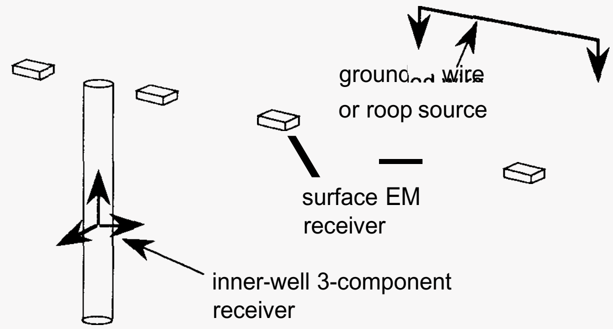

Figure 4. Schematic figure of Vertical Electromagnetic Profiling survey.

SEISMIC SURVEY METHODS

Various seismic exploration methods have been applied to geothermal fields. Each method is usually selected based on the purpose or stage of the exploration. In this survey project, micro-earthquake observation will be carried out to monitor hydrothermal fluid flow. In order to acquire the seismic wave speed distribution, vertical seismic profiling survey has already been conducted. Acoustic emission surveys during drilling will also be done for the same purpose.

Vertical Seismic Profiling Survey

As a part of another project, NEDO carried out a vertical seismic profiling (VSP) survey using WD-I in the end of 1994, from 0 to 1,400 m. The original purpose of conducting the VSP survey is to evaluate the effectiveness of the receivers developed throughout the project especially their performance under high temperature. However, by inversion analysis of this VSP survey, a profile of the neo-granitic rocks is expected to be imaged and the conditions of deep fracture systems will be evaluated before drilling reaches the neo-granitic rocks. This evaluation is quite important for an appropriate drilling planning as well as for the deep geological survey. The seismic wave speed distribution calculated from the VSP data will also be used for determination of the hypocenters of micro-earthquakes.

Micro-Earthquake Observation

Micro-earthquakes are good indicators of the existence of fractures in which hydrothermal fluids may flow. Figure Sa (Sugihara, 1993) shows the micro-earthquake hypocenters on a NW-SE cross section at the Kakkonda geothermal field. These micro-earthquake events occurred over the span of one year.

In the northwestern part of the field, micro-earthquake hypocenters spreads straight down to a depth of 4,000m. This suggests the development of a fracture system down to this level. Figure 5b shows the transition of micro-earthquake hypocenters after shut-in during a flow test. The micro-earthquake hypocenters move outward from the injection zone which can be identified in Figure 5c.

In this project, continuous observation of micro-earthquakes has begun since December 1, 1994. The network system of the micro-earthquake observation points had been renewed before the observation began. Two observation points in shallow holes were added to the original network on the east side of WD-1 (i.e. east edge of the Kakkonda field) where no standing observation center was sited. A shooting survey will also be conducted to acquire the subsurface distribution of seismic wave speed and to check the accuracy of the calculated locations of the hypocenters shown in Figure Sa.

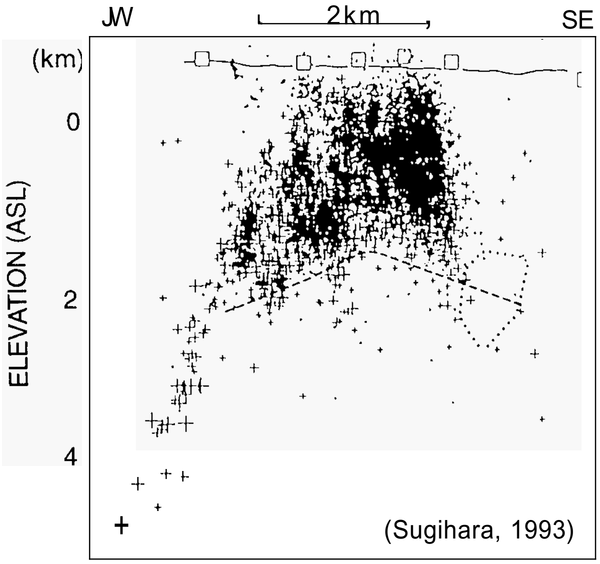

Figure 5a. Hypocenters of the micro-earthquakes occurred in the Kakkonda geothermal field in 1988. The broken line indicates the assumed profile of the top of the Neo-granitic pluton.

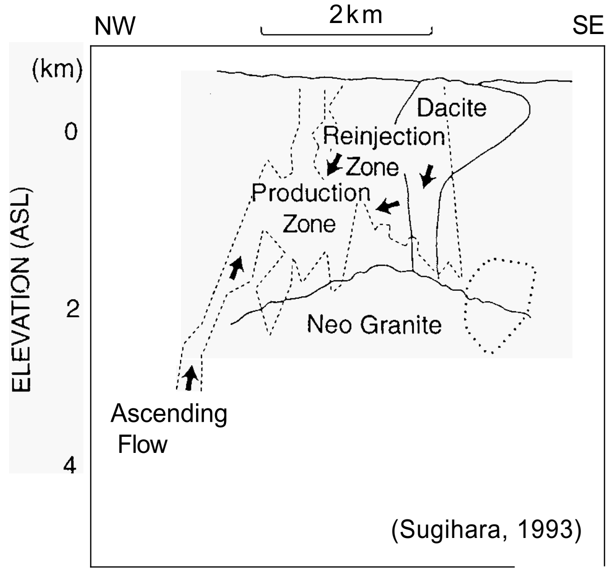

Figure 5c. Schematic cross-section of the Kakkonda geotheimal field based on micro-earthquakes and geological data.

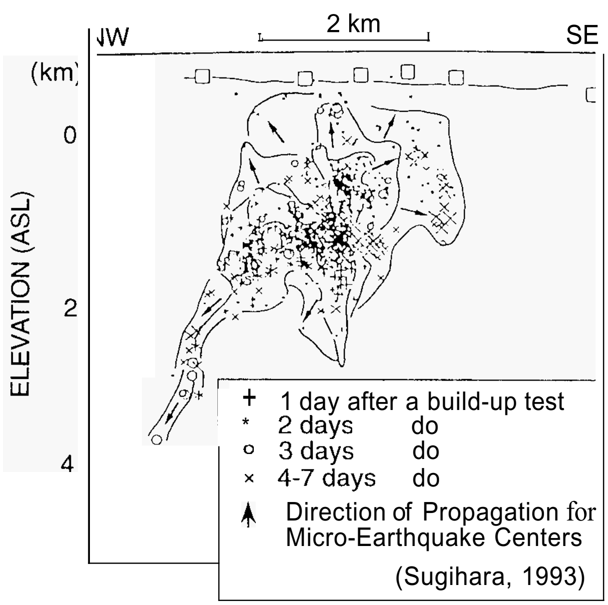

Figure 5b. Transition of the hypocenters of the micro-earthquakes after a build up test in Kakkonda

SUBSEQUENT SCHEDULE

The schedule of the survey project is shown in Table 1. WD-1 has been drilled to a depth of 1,505 m (M.D.). In FY-1994, after various kinds of borehole surveys, including VEMP, MAIL, CSMT and VSP, the drilling of WD-I will restart in January, 1995 with a larger rig which has an ability to bore down to 4,500 m. WD-I will be drilled to approximately 3,000 m by the end of May, 1995. Acoustic emissions during drilling will be observed at this time. After this drilling, resistivity surveys (MAIL and VEMP) will be conducted again to gain data at a deeper and thus wider range.

In FY-199.5, after a fluid injection test, the first flow test will be undertaken at around the 3,000 m level for three months with PTS logging, PT monitoring, tracer, and erosion and corrosion tests using test casing. After the test casing is withdrawn from the bottom of WD-I, the bottomholc will be stabilized by cementing. Then WD-1 will be drilled down by side track with pack-stock nearly from the bottom of the 13 3/8' casing pipe. This will be the most difficult operation of the entire drilling process.

The drilling from 3,000 to 4,000 m will restart in FY-1996 after stabilization of the drillhole following the first flow test. The drilling of this interval will be extraordinarily fascinating because the drillhole will go across many deep fractures suggested by micro-earthquake monitoring surveys (Sugihara, 1993). The third set of resistivity surveys will then be conducted after the drilling is over and when the drillhole has hit promising reservoirs. The successive flow test at this level is planned to be a longterm one. PT monitoring, tracer tests, and erosion and corrosion tests, etc., will also be conducted simultaneously. Integrated analysis will be conducted in the last two years of the project.

	1992	1993	1994	1995	1996	1997
Drilling and Surveys	600m	1500m	3000m		4000m	
Flow Test, etc.			at	3000m	at	4000m
Integrated Analysis						

Table 1. Schedule of the "Deep-seated Geothermal Resources Survey."

CONCLUSIONS

Three factors essential for deep geothermal resources, namely, heat supply from a heat source, hydrothermal fluid flow and its recharge system, and formation of fracture systems which make up geothermal reservoirs, will be investigated in this project.

As the latest knowledge in terms of geological and geophysical aspects taken in the survey project is added to the first geothermal model, the model becomes more reliable and useful for planning deep drillings and exploration. The effectiveness of the new exploration methods for deep geothermal resources, such as micro-earthquake activity, VEMP, and MAIL, will also be confirmed. Even though analysis methods are under study and the results are not clear yet, the criteria for applying these methods and their joint analysis will be developed throughout this project.

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