THE RESISTIVITY STRUCTURE OF THE DEEP GEOTHERMAL RESERVOIR IN KAKKONDA - THE EXPLORATION BY THE BOREHOLE EM AND MT/CSAMT SURVEY

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SUMMARY – Since 1992, NEDO has undertaken the Deep Seated Geothermal Resources Survey Project in Kakkonda (Iwate, Japan). The pilot survey well WD-la reached 3,729 m depth and 550 degrees C in 1995. In 1996, NEDO drilled a side-track well WD-lb and hit several high penneability zones. Geophysical surveys (MT, reflection seismic, micro-earthquake, etc.) and geophysical logging has been carried out by JMC and NEDO during field development and this project. We compiled and compared the results of MT, micro-earthquake and well data, with the results from new exploration techniques using electromagnetic utilizing wellbore methods named MAIL (Multi-frequency Array Induction Logging) and VEMP (Vertical ElectroMagnetic Profiling) that were developed in this project. The results suggest that there is high probability of open fractures in the region correlating with the steep resistivity gradient.

1. INTRODUCTION

The Deep-seated Geothermal Resources (DSGR) Survey Project for the Geothermal Prospecting Technology Verification Program has been carried out by the New Energy and Industrial Technology Development Organization (NEDO) since 1992. A deep geothermal survey well -WD-1a was drilled in Kakkonda (Iwate, Japan) and in 1995 it reached a depth of 3,729 m (bed temperature of 550°C) where it intersected the Kakkonda granite (Saito et al., 1996). In 1996, a side-track well WD-lb was drilled and a number of highly permeable zones were intersected. The Kakkonda geothermal field has been developed by the Japan Metal & Chemical (JMC) group to supply steam to the Tohoku Electric Power Company. Numerous wells were drilled in the area as part of the development of the geothexmal power Unit 1 (50 MW) and Unit 2 (30 MW) for exploration, production and reinjection ; a number of these also reached the Kakkonda granite. JMC has conducted geophysical surveys from the surface (MT, reflection seismic, gravity and micro-earthquake monitoring) and electric logging of most of the wells since 1973. As a result, there is an excellent data base for Kakkonda against which experimental data can be compared for the DSGR survey project.

In 1994 as part of the DSGR survey project, we carried out MT & CSAMT surveys along a line (6km) passing through well WD-1. In 1987, JMC conducted the MT survey independently. The combined cross-sectional results of the two MT surveys, together with the well data (electric logging and geological data) and micro-earthquake monitoring data were compared with the drilling and geologic data (Osato et al., 1996). In the next study, we expanded the area of investigation by including the past MT sounding points that had been surveyed by NEDO in the surrounding regions (Akitakoma area, Akita; East area of Tazawa lake, Akita; West area of Mt. Iwate, Iwate; and Yunomori area, Iwate). In addition, we compared the 3D resistivity structures obtained from MT 2D inversion analyses using the RRI inversion scheme (Yamane, et al., 1998) with the high permeability zones identified in drilling, geology, geophysics, and logging data of the WD-1b (Osato, et al., 1997). Results from new survey techniques in 1997 using electromagnetic borehole methods – MAIL: Multi-frequency Array Induction Logging (Sato, et al., 1996) and VEMP : Vertical Electro-Magnetic Profiling (Miura, et al., 1996) were also compared with the other results. Our information database (named "GEOBASE) allows the retrieval of subsurface information. All the data from the former surveys, including the lost water zones identified by spinner logging and electric logging data (long normal) of WD-lb, the top of the Kakkonda granite, nine cross-section maps (resistivity) of MT survey processed by the 2D inversion scheme (Yamane, et al. 1996), recent micro-earthquake data, gravity analyses (p = 2, 3), and MAIL logging and VEMP survey, were input into the database.

2. MAPPING METHOD

We employed a simple kriging method similar to that used by GSLIB (Deutsch and Journal, 1992) on GEOBASE. This method can deal with two-dimensional and three-dimensional geometric anisotropy. Although, four types of variogram models are available, spherical, exponential, Gaussian and power models, the present study used only the spherical model. The spherical model variogram can be given as a function of the distance (h) with the upper limit parameters of the variogram model (c: cil) and the distance at which the variogram reaches cil (a), as follows:

$$Y(h) = c \cdot Sph\left(\frac{h}{a}\right) \begin{cases} = c\left(1.5\left(\frac{h}{a}\right) - 0.5\left(\frac{h}{a}\right)^3\right) & \text{if } h \le a \\ = c & \text{if } h \ge a \end{cases}$$

In the present study, we conducted three-dimensional interpolation and three-dimensional representation by analysis of three-dimensional kriging data obtained fkom MT surveys and the geophysical logging data, including the subsurface information table. The variogram fiom the MT surveys was estimated fiom the data and those derived theoretically with parameters where $c = 2 \times 10^6$, a = 1,000, and anisotropy ratio of 2: 1 was apparent in the N20° E direction.

3. INFORMATION DATABASE OF THE KAKKONDA AREA

The data shown in Table 1 was available fiom GEOBASE for analysis of the resistivity structure in Kakkonda (Osato, et al., 1996). WD-1b well data and the results fkom reanalysis of the MT survey data, as shown in Table 2, were added to the database in 1997 (Osato, et al., 1997).

Figure 1 shows the survey lines for MT 2D inversion reanalysis.

Table 1 Original database in Kakkonda (1996)

Data type	Data description
Subsurface information (borehole data)	Existing wells (JMC) and the WD-1a (NEDO)
	Electric logging (long normal) (1973-1995, JMC and NEDO: WD-1a)
Three-dimensional discrete data	Cross section maps obtained by MT 2D inversion analysis (resistivity) - One cross section map along a 6 km line (1994, NEDO) - Four cross section maps (line - A,B,C,D) along 2 km lines (1987, JMC)
	Hypocenter of micro-earthquakes (1994-1995, NEDO)
Two-dimensional discrete data	Altitude (Kokudochiriin)
	Surface depth of the Kakkonda granite (1995, JMC)
Polygon data	Instrusive Rock (Matsuzawa Dacitic Intrusion & Torigoenotaki Dacitic Intrusion, JMC)

Table 2 Additional database in Kakkonda (1997)

Data type	Data description
Subsurface information (borehole data)	Lateral well WD- lb (NEDO)
	Electric logging (long normal), Depth of water loss zones (1996, WD-1b: NEDO)
Three-dimensional discrete data	Cross section maps obtained by MT 2D inversion analysis (resistivity) - Three cross section maps (line – 1,2,3) along 20 to 25 km long lines - Two cross section maps (line – E,F) along 1 to 2 km long lines (1995/1989/1987-1992/1988-1989, NEDO) and (1987, JMC)
	Hypocenter of micro-earthquakes (1994-1995, NEDO)
Two-dimensional discrete data	Gravity contour (ρ=2. 3) (1995, NEDO)

4. INTEGRATED ANALYSIS DIAGRAM

The following information was retrieved fiom the Kakkonda database: results of two-dimensional MT analysis; the location of the top of the Kakkonda granite; distribution of micro-earthquakes ; lost water zones of WD-lb; and well trajectories.

Based on this information, the following maps were compiled for integration:

(1) Plan maps at 500m, 1,000m, 1,500m, and 2,000 m below sea level
(2) Cross sections, N75°W-S75°E, running parallel to the Kakkonda river and passing through well WD-la
(3) A cross section, N50° W-S50° E, passing near WD-la and WD-lb well bottoms

5. ANALYSIS OF MT SURVEY DATA

Figure 2 shows the interpolated resistivity map using six lines of the MT 2D inversion analyses at 2,000 m below sea level with the top of the Kakkonda granite and the hypocenter distribution of the micro-earthquakes.

Figure 3 shows the Bouger gravity map (terrain density = 2.3). The Bouger anomaly gravity distribution in this area shows that the values decrease toward the south-east. A zone of high resistivity exists to the north-east, and another exists along the surface of the Kakkonda granite (the center right half of the figure). The Bouger anomaly of the Kakkonda granite (intrusive rock) is not much higher than that of the bedrock. Comparison of the Bouger anomaly gravity distribution and the resistivity structure shows that the high resistivity area surrounding the Kakkonda granite does not correspond with an area of high gravity. In addition, the resistivity generally tended to decrease fiom northwest to southeast, following the tendency seen in the Bouger anomaly data.

Figure 1. The survey lines for MT 2D inversion reanalysis in Kakkonda

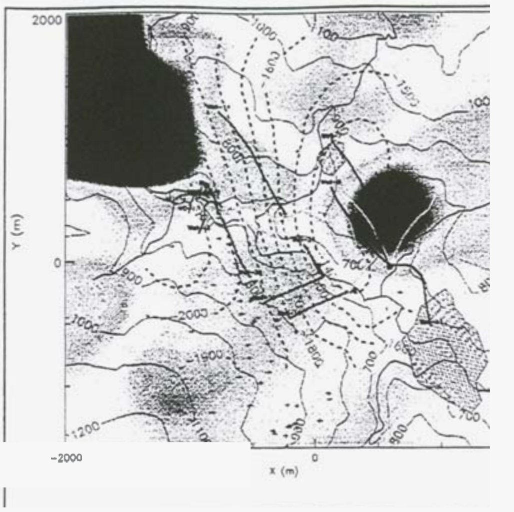

Figure 2. MT resistivity map (high values are dark=500m and low values are light =20m), showing the epicenter distribution of micro-earthquakes (+), the trajectory of the existing wells (white and black lines) at 2,000 m below sea level, and the top of Kakkonda granite (broken line).

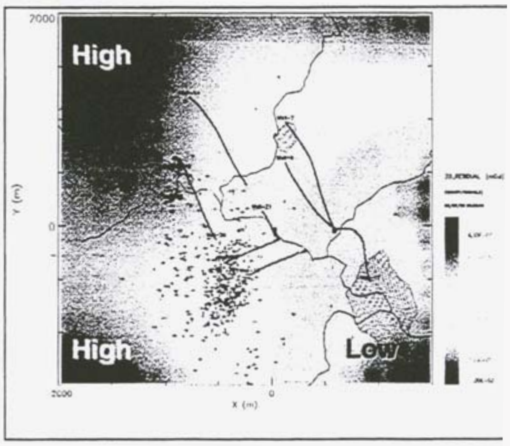

Figure 3. Bouger gravity map reduced using a terrain density of 23.

The gravity distribution suggests the existence of bedrock, or a high resistivity formation with a gravity signature similar to that of the bedrock, near the surface. Most of the wells are located over an area corresponding to a steep change from high to low resistivity, although the high resistivity areas to the northeast and in the central eastern section corresponding to the top of the Kakkonda granite had not been drilled.

From the distribution of the micro-earthquakes, micro-seismicity occurred in the zone extending from the steep resistivity area toward the low resistivity area, with very few earthquakes occurring in high resistivity areas of 150-200 Ωm or higher. As a result, it is highly probable that a group of fractures forming a geothermal reservoir exist, the center of which lies in the steep resistivity gradient between the high and low resistivity areas.

Figure 4 shows a cross section along the N75°W-S75°E line, which lies parallel to the Kakkonda River and passes through the site of WD-1a. Together with the MT resistivity distribution, the figure also shows the hypocenter distribution of the earthquakes (+) over a range with margins of 250 m along both sides of the cross section. The existing wells, the geological column diagram of the WD-la well, and top of the Kakkonda granite, where the depth was confirmed by drilling (dotted lines), are also indicated.

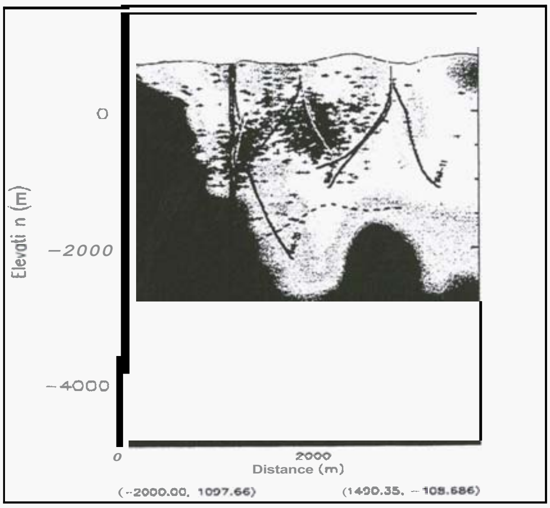

Figure 4. MT resistivity cross section (high values are dark=500m and low values are light =20m) along the N75°W-S75°E line. Also shown are the distribution of micro-earthquakes hypocenters (+), the trajectory of the existing wells (white and black lines) at 2,000 m below sea level, and the top of Kakkonda granite (broken line).

Figure 5 shows an enlarged cross section map along the N50° W-S50° E line, passing near the WD-la and WD-lb well bottoms.

Three lost water zones identified in spinner logging of WD-la under water injection are marked with filled circles. As can be seen from the figure, the WD-la well passed through the high resistivity zone protruding from the west side without hitting any lost water zones with open fractures. The WD-1b well intersected a lost water zone when it passed through a relatively low resistivity zone, intruding into the high resistivity zone on the west side at about 1,000 to 2,500 m below sea level. Micro-earthquakes frequently occurred in the shallow reservoir, around the margin of the high resistivity zone and extending horizontally from the west at about 800 m below sea level, over the relatively low resistivity zone.

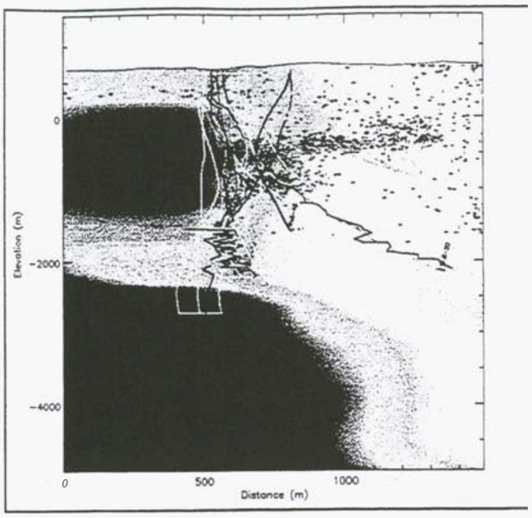

Figure 5 Cross section along the N50° W-S50°E line passing near the well bottoms of WD-1a and WD-1b showing three lost water zones (filled circles) and the electric logging (long normal) of WD-la, WD-lb, Well-19 and Well-20.

6. RESISTIVITY STRUCTURE ANALYSIS FROM ELECTROMAGNETIC SURVEY OF BOREHOLES

New borehole electromagnetic imaging surveys were carried out by development of MAIL (Milti-frequency Array Induction Tool) as a long offset multi-frequency array 3-component induction logging tool, and VEMP (Vertical Electro-magnetic Profiling Tool) as borehore to surface electromagnetic tomography. Both tools are based on the frequency domain EM method.

MAIL covers a range of 3 kHz to 42 kHz, and VEMP covers a range of 1 Hz to 128 Hz. MAIL is able to detect resistivity structures existing within a 6 to 8 meter radius of the well, while VEMP is used to survey resistivity structures existing between the grounded wire sources or loop sources in the surface and the borehole magnetometer installed in the well. These electromagnetic surveys were conducted in the unlined section of well WD-1b, between a depth of 2.2 km and 2.9 km, which was drilled in 1997 as a side-track well to WD-la (TD = 3,729m).

The VEMP survey was carried out by the installation of grounded wire sources at six separate locations. Figure 6 shows the arrangement of the grounded wire sources for the VEMP survey.

The analysis of MAIL logging was carried out by inversion analysis using the cylindrical 1D model. Figure 7 shows a diagram of the survey results of the MAE logging together with the electric logging (long normal) , lost water zones, and geological column of WD-1b.The result shows a good correlation with the electric logging.

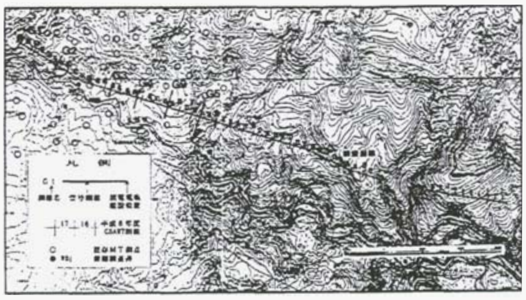

Figure 6 Layout of surface sources for the VEMP survey (G1,G2,G3,G4,G5,and G9 are the grounded wire lines) and the MT/CSAMT survey line in 1994

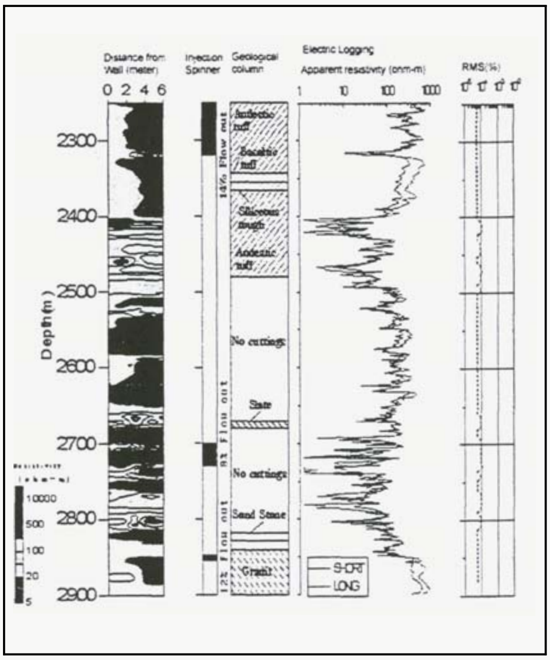

Figure 7 MAIL **logging resistivity image of WD-1b showing the geological column, long normal logging data, and lost water zones during drilling**

The results of the **VEMP** survey were processed by inversion analysis using the **2.5** FDM model. The results of the analysis were compared with data and geological maps obtained from previous geophysical surveys conducted in the **Kakkonda** area.

A comparison of the geophysical survey data from **NW-SE** cross section maps including the CDP cross section obtained using a high resolution seismic reflection method developed by NEDO (NEDO, 1997), and the hypocenter distribution of the micro-earthquakes obtained in the present project, and electrical logging (long normal) **data** of existing wells will be presented. The trajectories of existing wells (production wells, reinjection wells, and deep geothed exploration wells: WD- la and WD- lb), water loss zones of WD-1b **and** the microseismicity **are** compared to the seismic reflection survey.

The results show the following:

(i) A correlation between the boundaries of the structures obtained from 2.5D analysis of the VEMP survey data and the CDP cross section of seismic reflection prospecting.

(ii) Lost water zones at depth in WD-lb and Well-19 correlate with the low resistivity structures fiom **VEMP.**

(iii) A sensitivity check on the reliability of the analysis of the **VEMP** survey **is** required **as**, there was insufficient data obtained for depths above 2,200 m due to the conditions of the wells.

7. CONCLUSIONS

Data from **six** cross section maps obtained by MT 2D inversion image (2D cross section analysis) were processed to 3D 'interpolated' resistivity distribution by krigging of the database - GEOBASE. When the logging **data** and micro-earthquake data were compared with the 3D resistivity structure that was obtained from MT 2D inversion *images,* the VEMP resisitivity image, and the MAIL resisitivity image, and the lost water zones, micro-earthquake activity correlate with relatively low resistivity values and mainly occurred in a region showing a steep resistivity gradient (a resistivity discontinuity); this area of correlation extends **fiom** the high resistivity area in the west toward the low resistivity range in the east. These results suggest the development of fractures in the steep resistivity gradient region is highly probable.

8. REFERENCES

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