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EXPLORATION OF POTENTIAL FRACTURES BY WATER INJECTION OPERATIONS

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ABSTRACT

An advanced geoelectrical method for fracture imaging has been developed for monitoring of fracture creations and propagation in related to the Hot Dry Rock geothermal power project at the Ogachi area by the Exploration Geophysics Laboratory in Kyushu University. The method named as Fluid Flow Tomography (FFT) utilizes a casing pipe itself as a charged current electrode instead of a buried point source used for the mise-a-la-masse method. The method has been applied to monitor fluid flow behavior during massive hydraulic fracturing operations for direct imaging of potential fractures. In the Hatchobaru geothermal field, a large amount of poisonous gas (H_2S) was blowing out around the depth of kick off point of a directional borehole. Therefore, two sidetracks were examined for deviating from the fracture, however the results were unsuccessful and drilling operations were stopped. Finally, the FFT survey was applied to determine the strike and dip of major fractures from 3D inversion of SP data in order to design a casing program. This paper presents a case study of the FFT survey applied to an exploratory drilling at a virgin area in the Hatchobaru geothermal field, Oita, Japan.

1. INTRODUCTION

An early application of the mise-a-la-masse (MAM) method was described by Conrad Schlumberger for mineral explorations. The method utilizes a buried point source of current within the target and another current electrode placed on the ground surface. The method is one of hole-to-surface measurements, and then may be classified as modern electrical tomography. However, the MAM method has some limitations for application to geothermal exploration because of the high temperature of boreholes. Therefore, we have used a casing pipe as a line source of current instead of a buried point source.

The improved MAM method has been used for direct imaging of conductive and resistive targets because of its better resolution and simple fieldwork than any other geoelectrical method. However, knowledge of fluid flow behaviors and man-made fractures associated with hydraulic fracturing operations has been required to monitor continuously the physical properties in the subsurface formations.

Therefore, we have developed an automatic recording system controlled by a personal computer for use at the HDR project (Kaieda, et al., 1995) as shown in Figure 1.

2. FLUID FLOW TOMOGRAPHY SURVEY

In the FFT method, a charged current electrode C_1 is connected to the wellhead of a casing pipe of an isolated well in a central part of the surveyed area. The distant earthing current electrode C_2 is placed at an infinite distance away from the charged current electrode. The base potential electrode P_2 is also placed at a distance greater than the length of casing pipe from the charged well on the opposite side to the cable connected to C_2 electrode in order to minimize electromagnetic coupling effects.

In the conventional mise-a-la-masse survey, one potential electrode P_1 is moved along traverse lines set in a grid or radial pattern. However, in the FFT survey, multiple potential electrodes such as 30, 60, and 120 channels are placed on a grid array or a radial pattern in order to measure continuously the transient phenomena as a function of time.

A commutated electric current of a few ampere intensity, which has a frequency of 0.1 Hz is introduced into the earth by a conventional transmitter for dc resistivity measurements.

The resulting voltages are continuously measured by a digital recording system with a sampling rate of 2 seconds controlled by a personal computer on the survey site.

The observed potentials are separated into spontaneous polarization potentials (SP) and charged potentials (CP) by the digital data processing using a running average method.

The charged potentials are converted to apparent resistivity by multiplying by a geometric factor for a line source equation. Self potentials which may be produced by streaming potentials are interpreted by the numerical modeling and inversion analysis based on a three-dimensional model by data processing (Mizunaga, et al., 1996) as shown in Figure 2.

3. NUMERICAL SP SIMULATION

Spontaneous polarization anomalies due to streaming potential effects have been studied by many researchers. The theory of irreversible thermodynamics in inhomogeneous media was applied to the problem of SP anomalies due to the electrical effects of pressure, temperature and chemical potential gradients within the earth. The cross coupled equations for fluid flow and electric current are expressed as follows (Fitterman, 1979):

$$S_1 = -C_{11}\nabla P - C_{12}\nabla\Phi \qquad (1)$$
$$S_2 = -C_{21}\nabla P - C_{22}\nabla\Phi \qquad (2)$$

where S_1 is the fluid flux, S_2 is the current density, P the fluid pressure, Φ the electric potential and C_{ij} the generalized conductivity. More specifically, C_{22} is the electrical conductivity s , C_{11} the hydraulic permeability k , C_{21}/C_{22} is the streaming potential coefficient and C_{12}/C_{11} is the osmotic coefficient. A total electric potential is defined as:

$$S_1 = -(k/m)\nabla P \quad (3)$$
$$S_2 = -C\nabla P - s\nabla\Phi \quad (4)$$

The numerical results of SP distribution on the ground surface for a generalized inclined fracture show that the anomaly pattern are generally the same as the one for a horizontal fracture, and it is interesting to note that the location of the maximum (+) and the minimum (-) values appear above the edges of the anomalous body (Masuda et al., 1997).

4. FFT FIELD SURVEY

High quantitiesof hydrogen sulphide gas had been blowing out during the course of drilling of an exploratory borehole (H-28) around the kick off point depth at a virgin area in the Hatchobaru geothermal field (Figure 3).

Therefore, two sidetracks from the kick off point depth of H-28 borehole were examined in order to avoid the harmful gas fractures.

However, these drilling results were unsuccessful. Therefore, in order to locate the major potential fractures directly in three-dimensions, the FFT survey was conducted on the drill site of HT-28.

In the FFT survey, multiple potential electrodes (30) were placed on the drill site and the potential distributions on the ground surface were continuously measured with 2 seconds interval for about 2 hours (Figure 5). The flow rate of water injection to the exploratory well H-28 during massive water injection operations is illustrated in Figure 5.

It was confirmed that self potential variation correlates with a flow rate during water injection operations as shown in Figure 6.

Therefore, it was proved that fluid flow fronts and injected water distribution could be evaluated by the time sliced data obtained with the present Fluid Flow Tomography (FFT) system.

5. 3D INVERSION OF SP DATA

Three-dimensional distribution of major fractures can be determined by the source distributions derived from the 3D inversion of SP data (Masuda et al, 1997).

Source distributions are derived from simple fracture models such as a point source or a line source based on a potential theory.

In this case study, fracture planes can be calculated from three depths of lost circulation zones by the straight hole drilling and two sidetracks of the H-28 borehole (Figure 7).

The strike and dip of the fracture plane determined by the FFT method coincided with the drilling results.

6. CONCLUSIONS

In order to evaluate a potential fracture of a gas reservoir, the FFT survey has been conducted during the course of drilling in a virgin geothermal area. Distribution and dip of fractures were determined by the 3D inversion of SP data.

Straight hole and two sidetracks of H-28 were already carried out previous to the FFT survey. Therefore, strike and dip of the major fracture plane could be calculated mathematically. The calculated strike and dip of the major fracture plane coincided that determined by drilling.

Finally, a drilling program of a fourth directional borehole was carefully designed according to the result of 3D inversion of SP data derived from the FFT survey. The resulting directional borehole was successfully completed and became the first production well in the southern part of Hatchobaru geothermal field.

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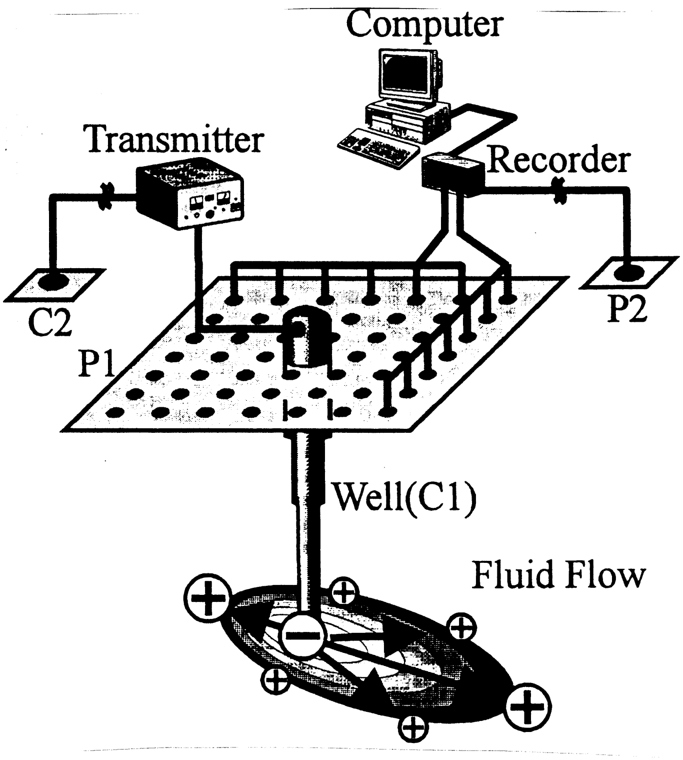

Figure 1. Fluid Flow Tomography system.

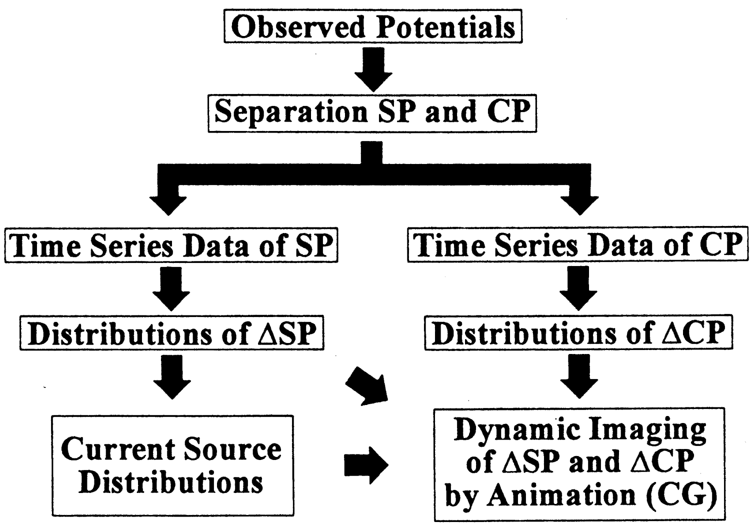

Figure 2. Data processing for Fluid Flow Tomography.

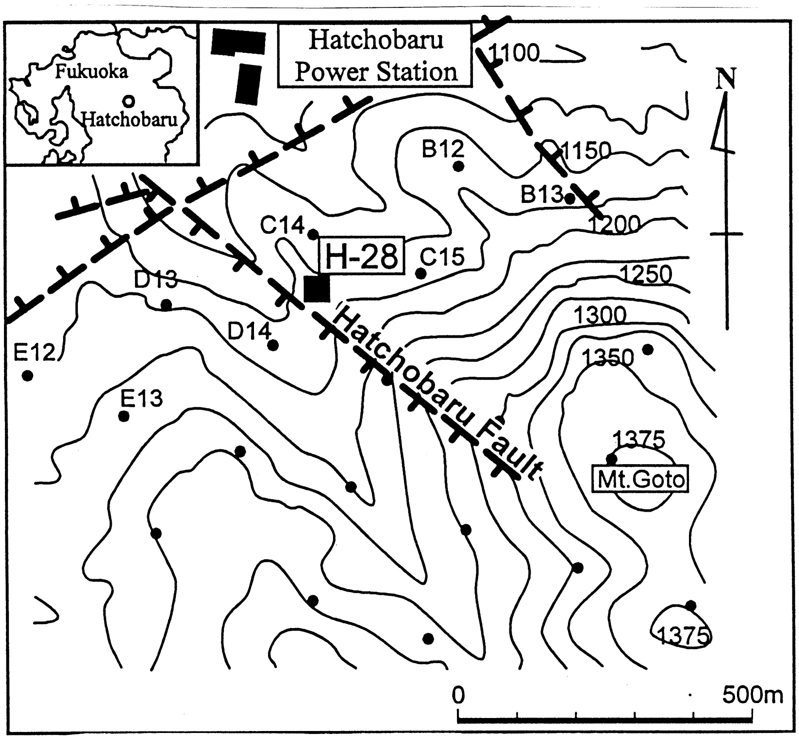

Figure 3. Location of H-28 exploratory borehole in Hatchobaru area.

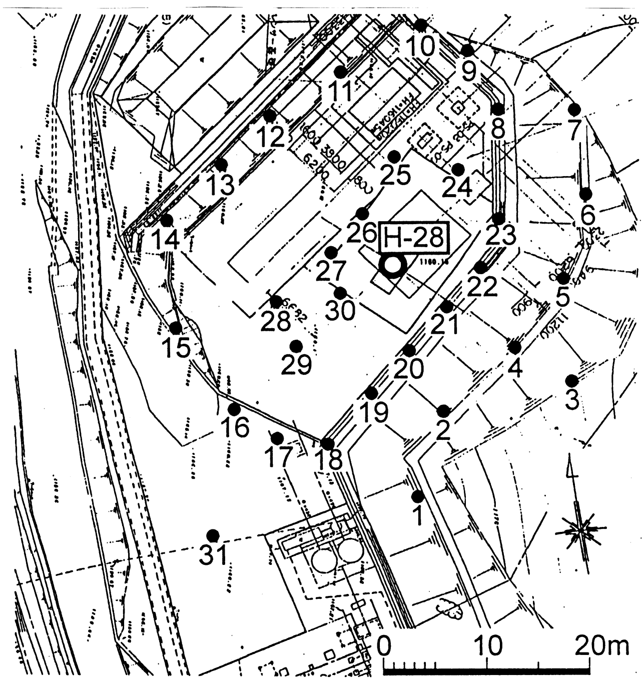

Figure 4. Location of multiple potential electrodes for FFT survey.

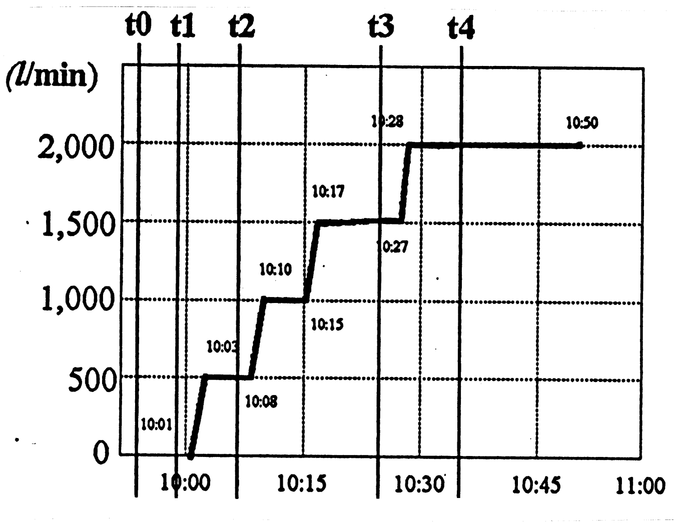

Figure 5. Flow rate of water injection with a function of time.

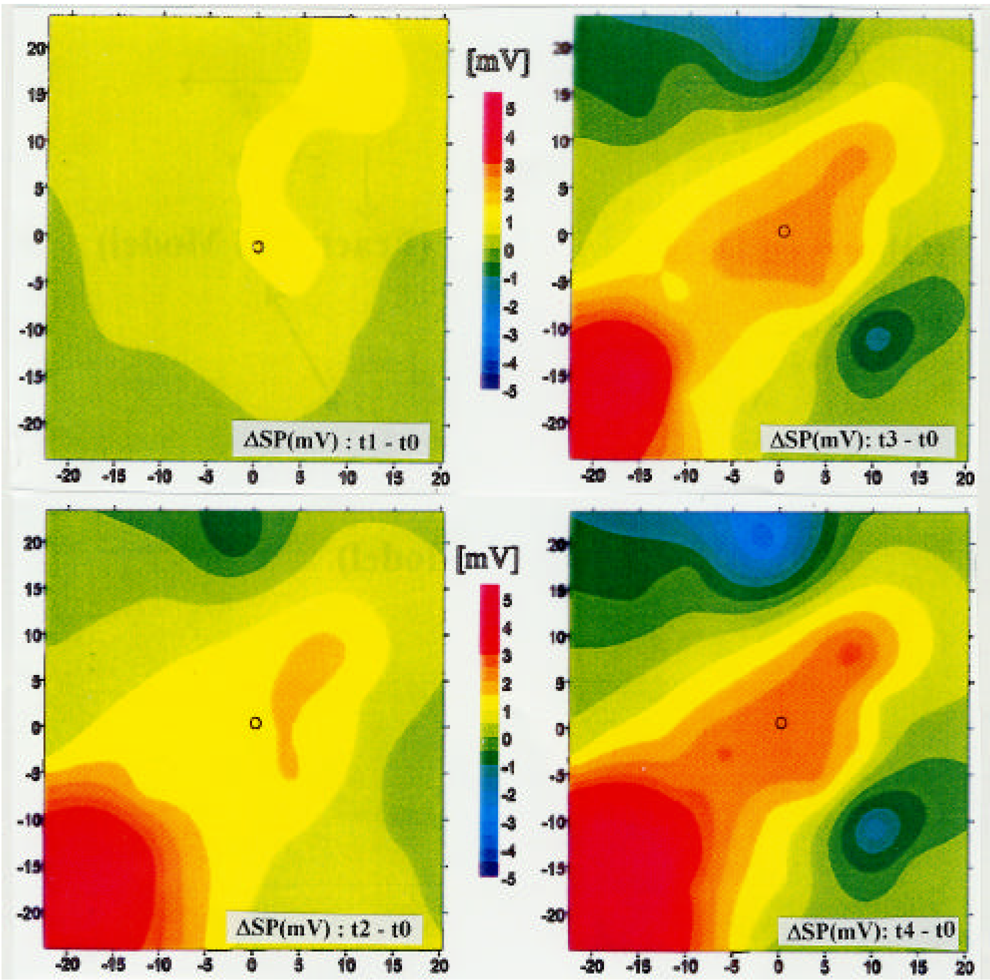

Figure 6. Residual SP variation with a function of time observed during water injection into H-28 exploratory borehole in Hatchobaru geothermal area.

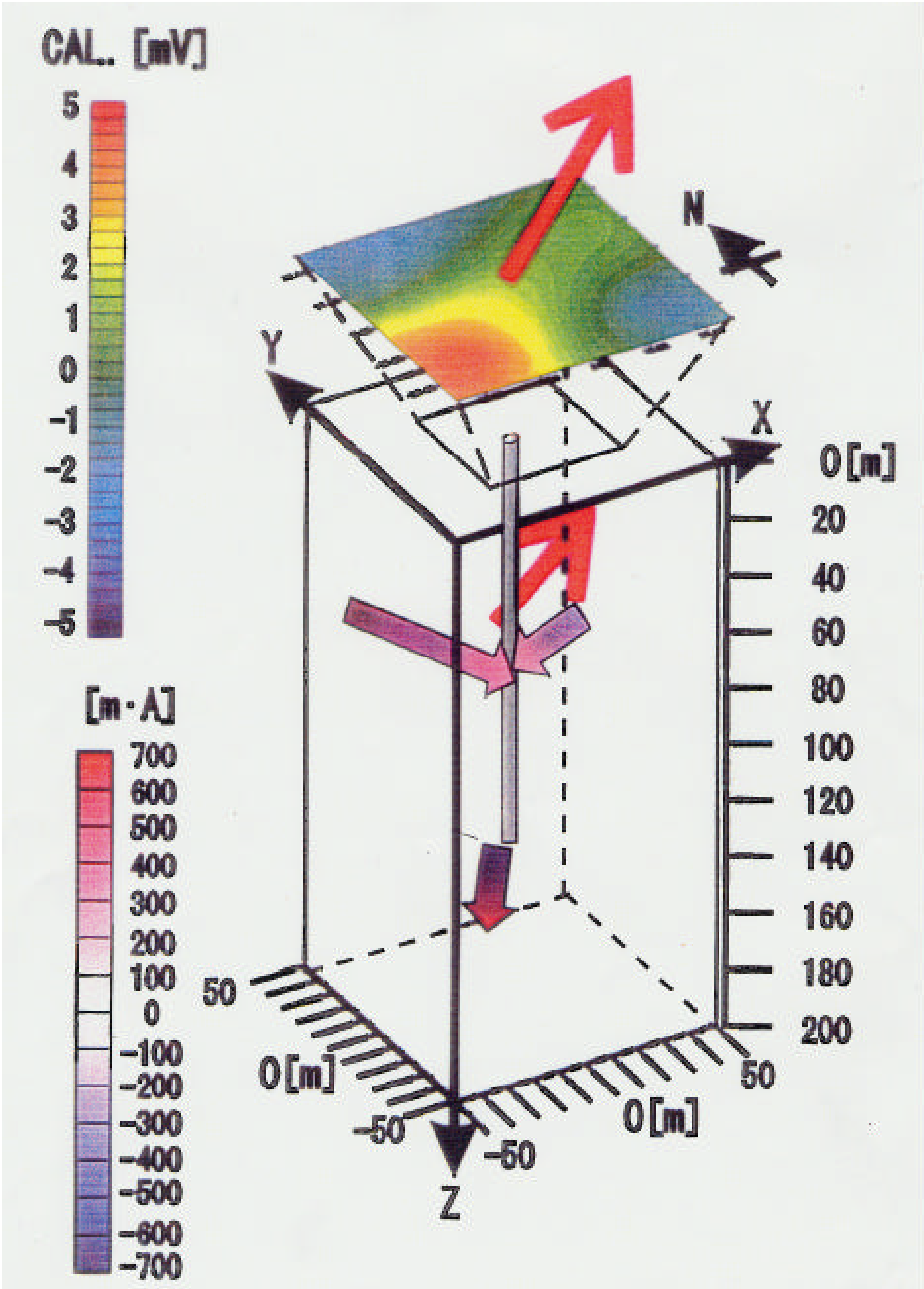

Figure 7. 3D location of major fractures determined by the FFT survey.