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3D MODELING AND INVERSION OF FLUID FLOW TOMOGRAPHY DATA

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ABSTRACT

An advanced geophysical technique called as Fluid Flow Tomography (FFT) method for direct imaging of fluid flow behaviors in reservoirs has been developed by the Geophysical Exploration Laboratory of Kyushu University. In the FFT method, fluid-flow fronts in the subsurface can be continuously visualized as a function of time from the transient phenomena of electric potential data observed during dynamic reservoir stimulations such as hydraulic fracturing, reinjection and swabbing operations for a well completion. SP anomalies for various fractures have been investigated with a numerical simulation for various 3D anomalous fractures. It is confirmed that the fluid flow fronts can be evaluated with a function of time by the 3D inversion of SP data during injection operations on the Hot Dry Rock geothermal power project at Ogachi area in Japan. The various computer programs developed for the FFT method can be directly applied to evaluate the electrical resistivity data for various electrode arrangements of electrical tomography, spontaneous potential method and electrical logging data.

1. INTRODUCTION

Various geophysical exploration techniques have been applied to the problem of monitoring geothermal and oil reservoirs. The most used geophysical methods are seismic, gravity, electromagnetic and mise-a-la-masse methods of geophysical explorations. An early application of the mise-a-la-masse method is described by Conrad Schlumberger for mineral explorations.

This method utilizes a buried point source within the target and another current electrode placed on the ground surface at an infinite distance away from the source. The mise-a-la-masse method may be classified into an electrical tomography because of hole-to-surface measurements. In a similar practical application to high temperature boreholes such as geothermal wells, we have used a steel casing pipe as a line source of current instead of a buried point source of current in a bottom of borehole (Ushijima,1989).
The improved method (line source–to–surface) has been widely used for conductive and resistive targets because of its better resolution properties and simple field works than any other geoelectrical methods.

However, knowledge of fluid-flow behavior and man-made fractures associated with hydraulic fracturing operations has been required to monitor the relative changes of physical properties of targets. Therefore, we have developed an advanced geoelectrical method called as the Fluid Flow Tomography (FFT) system in order to detect and monitor a moving target as a function of time as shown in Figure 1.

The injected fluid-flow can be continuously traced and visualized by making contour maps of residual self potentials and changes of apparent resistivity distributions observed at multiple stations (120 channels) with a personal computer on the survey site. In the system, data acquisition is automatically conducted and time series data are stored on floppy diskettes of a personal computer.

2. NUMERICAL SIMULATION OF SP

Spontaneous Polarization (SP) anomalies have been studied by many researchers since 1936. The theory of irreversible thermodynamics in homogeneous media has been applied to the problem of SP anomalies due to the electrical effects of pressure, temperature and chemical potential gradients within the earth.

The transient phenomena can be explained by the crosscoupled equations for fluid flow and electric current (Fitterman, 1979). SP simulation results over an anisotropic fractured model is illustrated in Figure 2 (Mizunaga et al., 1991).

It is recognized that the anomaly pattern are generally the same over an anomalous body and the location of the maximum positive value and the minimum negative value appear on the absolute edges of the targets. Therefore, distribution of fractures can be evaluated by 3D inversion of time sliced data.

3. INTERPRETATION OF SP DATA

In order to discuss the self-potential anomalies due to a streaming potential, we have to consider a simple fracture model through which fluid-flow in and fluid-flow out (Ushijima, et.al.1992). The flowing-in fracture is estimated to the porous media of the reservoir and acts as a channel of a downward flow of fluids in an injection well.

Drastic assumptions are made to analyze the fluid-flow behavior. All the openings of fractures on the reservoir can be treated as simplified models such as a point source or a line source of current as shown in Figure 3.

According to the potential theory and the principle of superposition, we can derive the total electric potential by using a point source of current and a line source of current under considerations (Masuda, et al., 1997).

An automatic iterative interpretation by the nonlinear least squares method has been developed for the interpretation of geoelectrical sounding data. Inversion is performed by the algorithm of Marquardt method with measured SP data, fitting the calculated to the observed data.

4. FIELD SURVEY AT OGACHI HDR SITE

The FFT survey has been conducted during hydraulic fracturing experiments together with AE measurements at Ogachi Hot Dry Rock Geothermal Power Project by the Central Research Institute of Electric Power Industry since 1990 (Figure 4).

In Ogachi area, the injection borehole was drilled to the depth of 1,000m and the formation temperature of the terminal depth was 224 ºC. The injection borehole was a barefoot completion for subsequent hydraulic fracturing operations. Hydraulic fracturing operations were conducted by two stages at depths of 990-1000m and 711-719m. In the first stage of fracturing, massive water was injected with a flow rate of 1～100 liter/min at the wellhead pressure of 0.1 ～ 1 MPa. In the second stage of fracturing at a depth of 711-719m, massive water was injected with a flow rate of several 100 liter/min. The maximum wellhead pressure of 26 MPa was observed at a flow rate of 490 liter/min (Kaieda, et al., 1995).

SP monitoring survey has been conducted before and during the two stages of fracturing operations together with AE observations in order to evaluate fracture initiation and fracture propagation. Dipole anomalies were observed and propagated to the surrounding zone with the progress of massive fracturing operations.

Current source distributions determined by 3D inversion of SP data are coincided with AE hypocenters during the massive fracturing operations at Ogachi area.

Therefore, fluid flow fronts and the injected water distribution could be visualized by SP distributions as a function of time during fracturing operations (Ushijima et al., 1994). The strike and dip of the major fracture could be evaluated by the source distribution derived from 3D inversion of SP data as a function of time.

3D inversion results of SP data at the time 22:52:31 on 1 July in 1993 for the second stage of fracturing were illustrated together with hypocenter distributions estimated by the acoustic emission (AE) measurements (Figure 5).

5. COCLUSIONS

In order to image fluid flow behaviors in an unsteady condition of reservoirs, an advanced geoelectrical method named as a Fluid Flow Tomography method was developed by the geophysical laboratory of Kyushu University. It is concluded that the fluid flow behaviors according to the fracture creation and propagation in the reservoirs can be visualized by monitoring of the SP distributions as a function of time.

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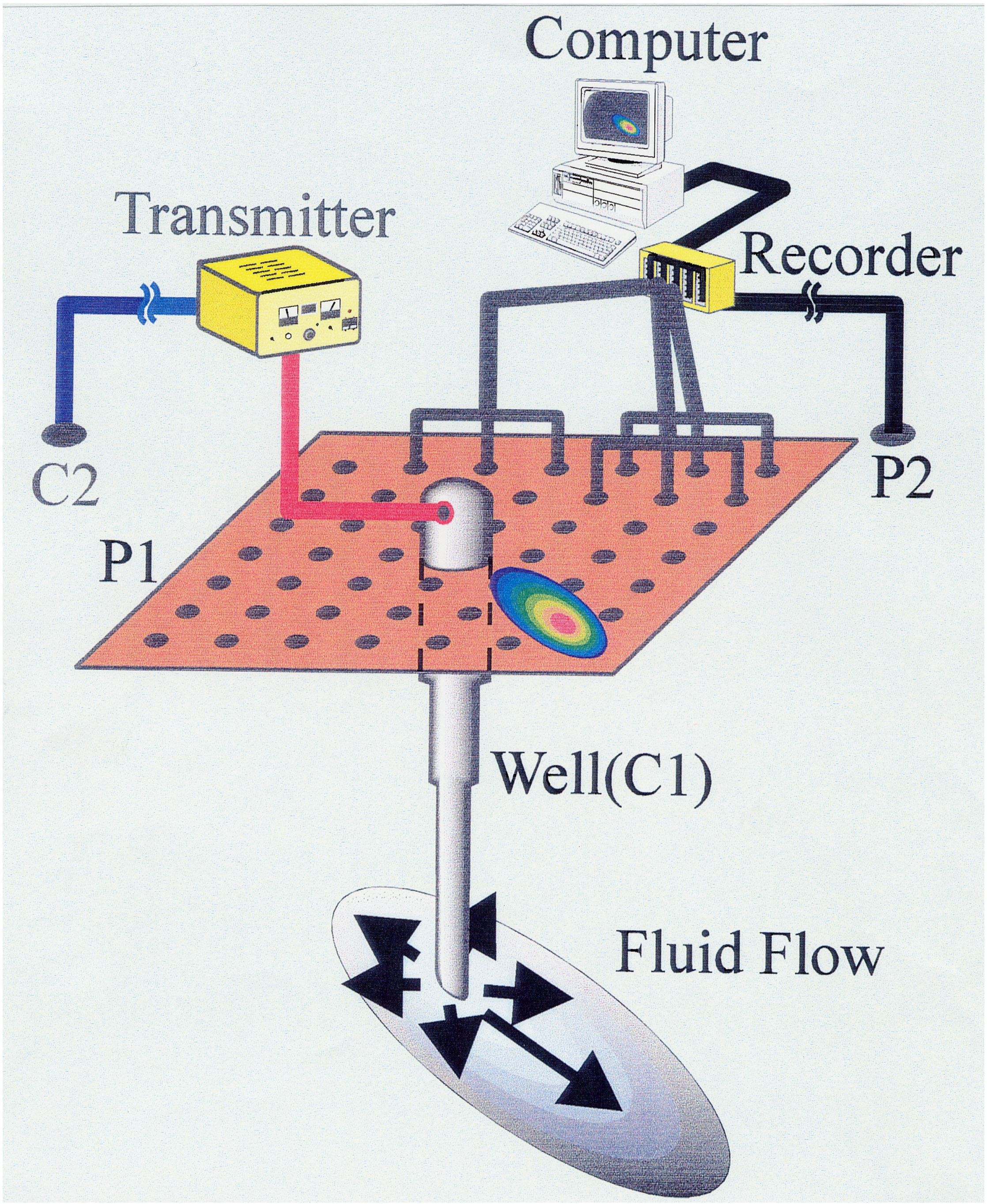

Figure 1. Field Layout of Fluid Flow Tomography (FFT) measurements.

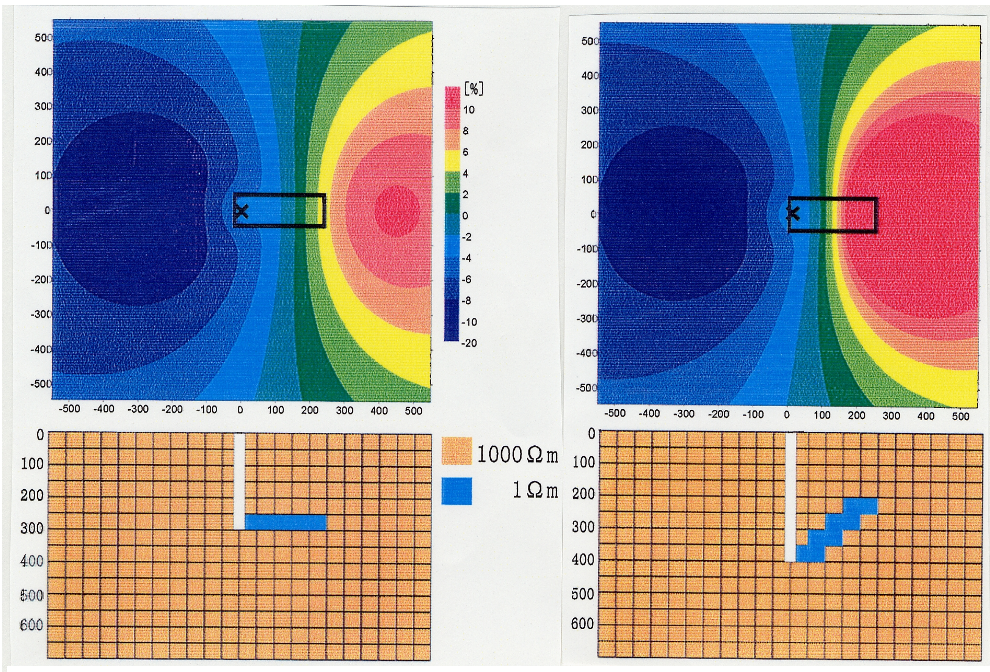

Figure 2. 3D simulation of SP for anisotropic horizontal and inclined fractures.

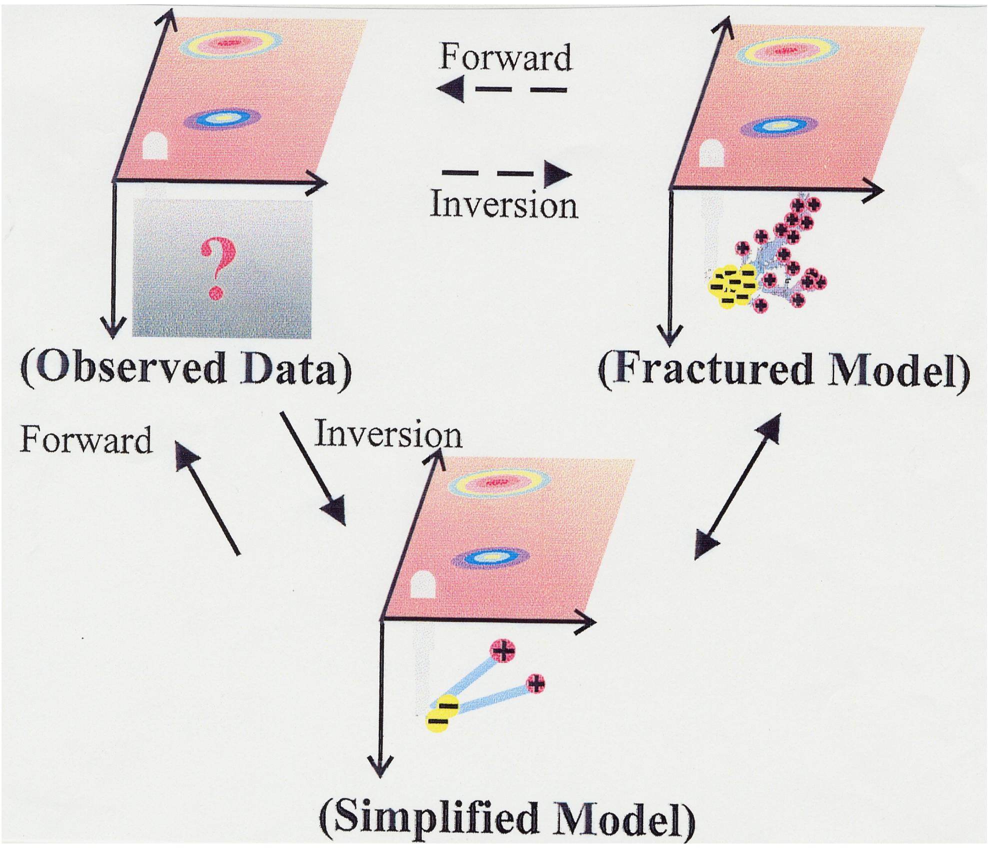

Figure 3. Interpretation of SP for imaging fractures.

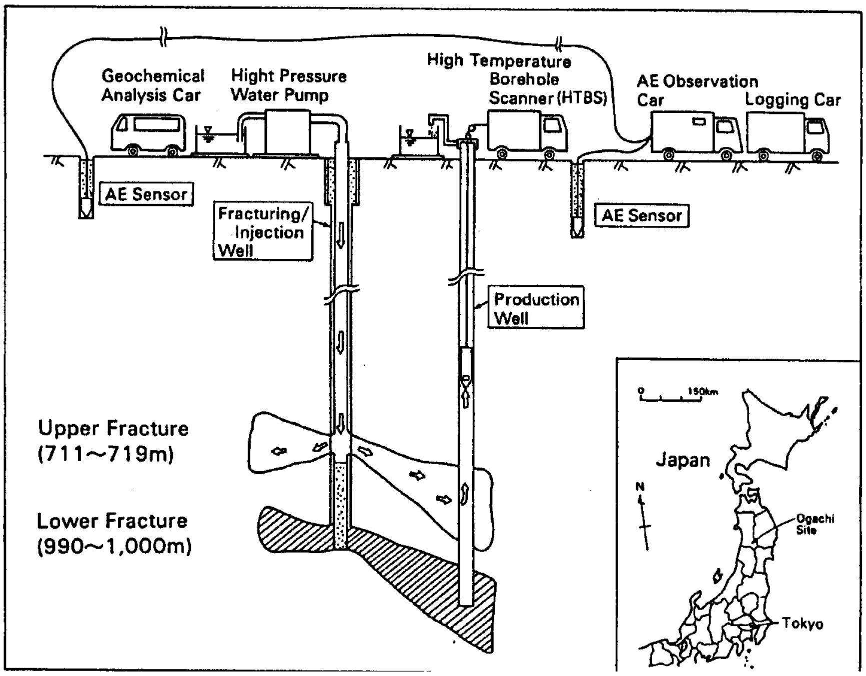

Figure 4. Ogachi Hot Dry Rock Geothermal Power Project (CRIEPI)

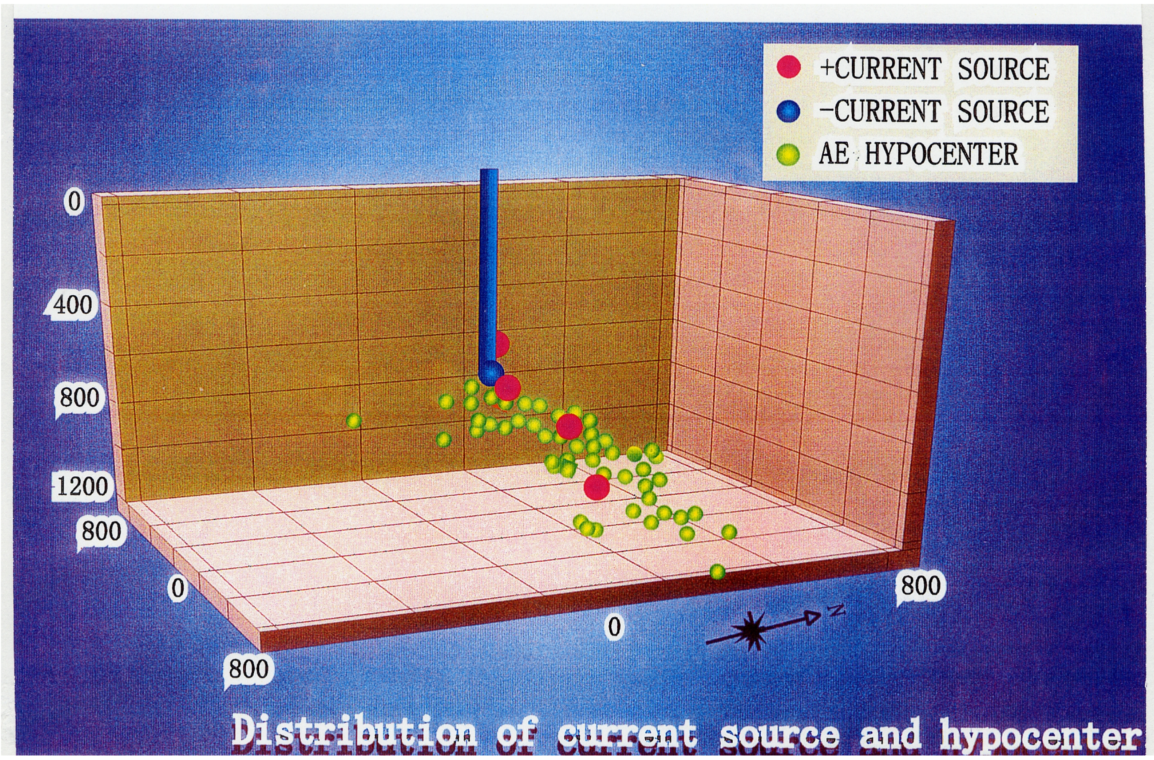

Figure 5. Current sources distribution determined by 3D inversion of SP data with AE hypocenters during second stage fracturing operations at Ogachi area.