

## **DIRECT IMAGING FRACTURES BY A 4-D GEOELECTRICAL TECHNIQUE AT SUMIKAWA GEOTHERMAL FIELD, JAPAN**

Tetsuo Aono, Hideki Mizunaga and Keisuke Ushijima

Kyushu University  
Hakozaki, Fukuoka  
812-8581, Japan

e-mail: ushijima@mine.kyushu-u.ac.jp

### **ABSTRACT**

The Sumikawa geothermal field is located in the Hachimantai volcanic region of northeastern Japan, where the Sumikawa geothermal power station has been operated since 1995. An advanced geophysical technique has been applied to image major fracture distributions at the Sumikawa area. The 4-D technique named as the FFT method (Fluid Flow Tomography) has been developed by Engineering Geophysics Laboratory of Kyushu University for imaging transient phenomena as a function of time. Subsurface resistivity structures could be determined from 3-D inversion of the mise-a-la-masse data, while fracture distributions could be estimated from 3-D inversion of SP (Self Potential) data using time series data obtained by the FFT method. It is concluded that distribution of potential fractures in the Sumikawa geothermal field were delineated and drilling programs were proposed for further developments of production and reinjection wells based on the joint interpretation of apparent resistivity and SP data obtained from the 4-D geoelectrical technique.

### **INTRODUCTION**

The Sumikawa geothermal field is located in the Hachimantai volcanic region of north eastern Japan, where there are active volcanoes, hot springs and fumaroles, as well as Ohnuma, Matsukawa and Kakkonda geothermal power plants. The Sumikawa geothermal power station has been jointly

developed by Mitsubishi Materials Corporation (MMC) with Tohoku Electric Power Inc., and operated since 1995. A Fluid Flow Tomography method using the S-3 well has been conducted in conjunction with a periodical inspection of the geothermal power plant. Charged potentials using a casing pipe of the S-3 well as a current electrode and streaming potentials during reinjection and

production operations were measured at multiple potential electrodes on the ground surface surrounding the well. Subsurface resistivity structure of the area could be determined using apparent resistivity data derived from the mise-a-la-masse data using a line source, while distribution of potential fractures could be estimated by 3-D COP inversion analysis using SP data as a function of time.

### **SUMIKAWA GEOTHERMAL FIELD**

The Sumikawa geothermal field is located in the Sengan geothermal area, where the various researches of geology, geochemistry, hydrogeology and geophysics had been conducted by the Geological Survey of Japan and NEDO under the sunshine project promoted by the MITI. The tectonics of the Hachimantai region is characterized by block movements and graven structure with a north-south trend as shown in Figure 1. The field survey layout is shown in Figure 2. The stratigraphy of the Sumikawa field consists of Quaternary volcanic rocks, lacustrine sediments, and Tertiary formations intruded by granitic rocks. The pre-Tertiary basement has not been reached by geothermal drillings (Ariki, et. al., 2000). The hydrothermal system occurs under lacustrine sediments and a shallow zone of hydrothermal alteration, which act as the cap rock of geothermal reservoirs.

Resistivity structures are obtained by two-dimensional (2-D) inversion of MT and CSAMT data (Uchida.et.al., 1995).

The resistivity model is characterized by a very low resistivity ( from 1 to 3  $\Omega$  m ) cap rock beneath a resistive layer and rather high resistivity layer of reservoirs ( on an order of 100  $\Omega$  m ). The very low resistivity of the cap rock is due to clay minerals such as montmorillonite.

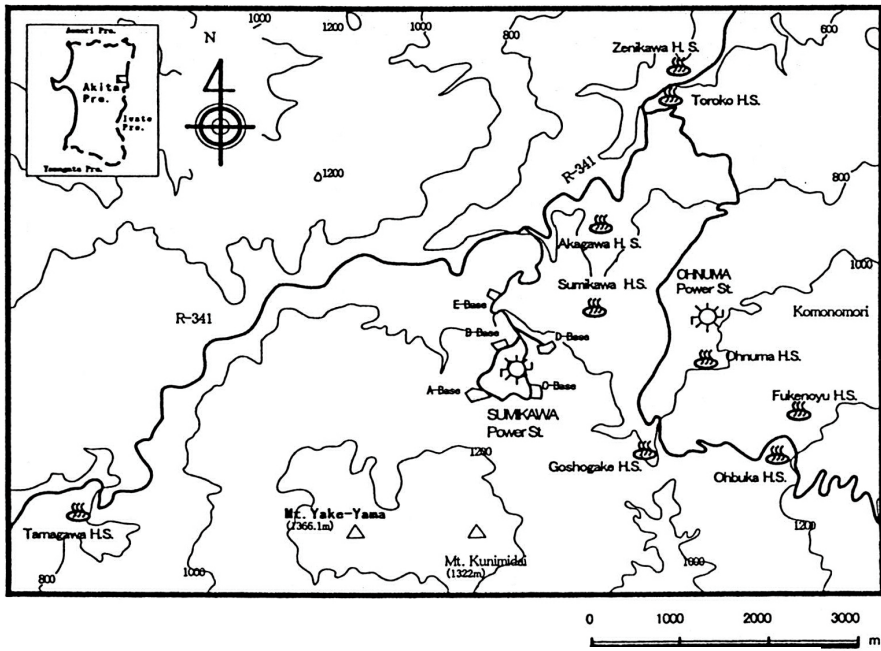


Figure 1. Location map of Sumikawa geothermal

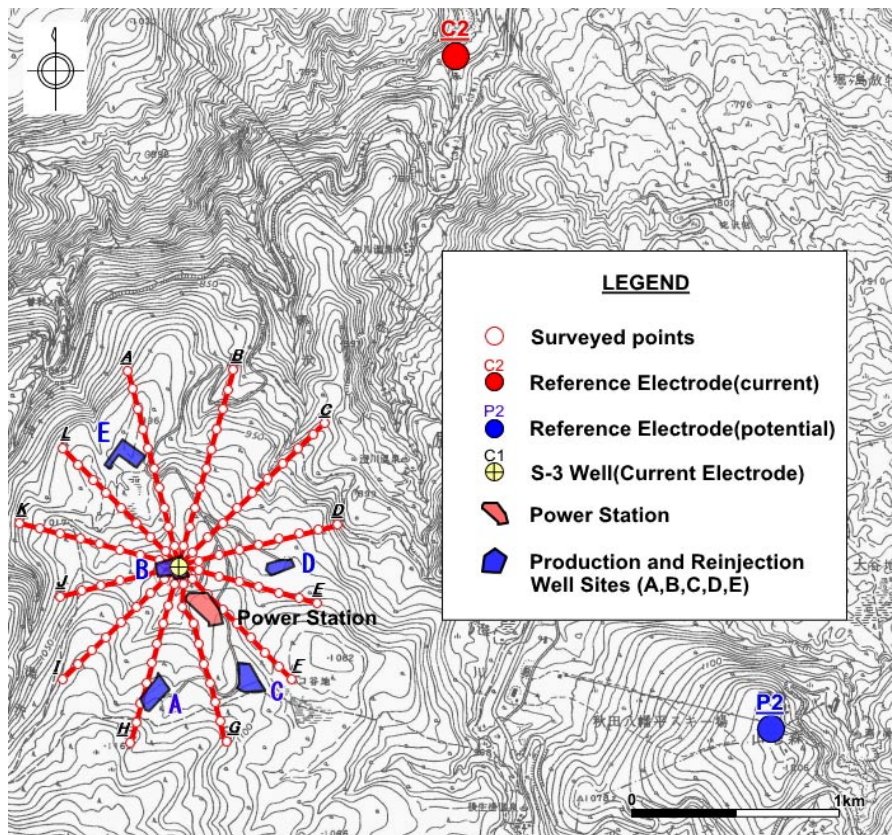


Figure 2. Electrode array of FFT survey in the Sumikawa area.

## 4-D GEOELECTRICAL TECHNIQUE

An advanced geoelectrical technique for imaging potential fractures has been developed by Engineering Geophysics Laboratory of Kyushu University (Ushijima, et. al., 1999). The method, fluid-flow tomography (FFT), has been applied to monitor fluid-flow behaviors during massive water/steam injection and production operations through a borehole.

Figure 3 shows a field layout of FFT survey. A charged current electrode (C1) is connected to the conductor casing of the S-3 well. The earthing electrode (C2) is fixed at 3 km away from the charged electrode. The base potential electrode (P2) is also fixed 3 km away from the well and on the side opposite the C2 cable line to minimize electromagnetic coupling effects. A potential electrode (P1) is moved along a traverse line for the conventional mise-a-la-masse survey, while multiple potential electrodes are used for the FFT survey. An electric current of 1 - 5 amp and a frequency of 0.1 Hz are introduced into the earth by a conventional transmitter of electrical resistivity surveys.

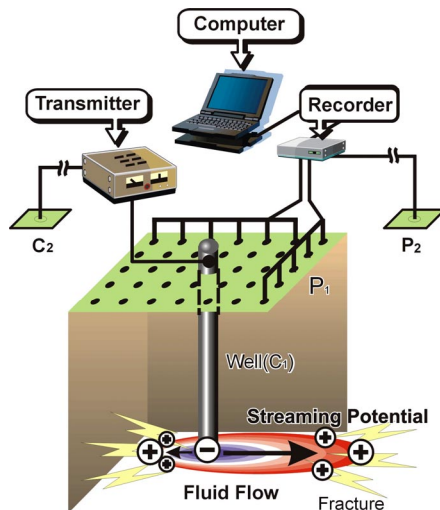


Figure 3. Field layout of FFT measurement.

## DATA PROCESSING OF FFT SURVEY

Potential distributions on the ground surface are continuously measured by a digital recording system controlled by a personal computer on the survey site. The charged potentials are converted to apparent resistivity values multiplying by a geometric factor of the mise-a-la-masse method. Self potentials due to streaming potentials separated from observed data are measured and interpreted by the flowchart of data processing as shown in Figure 4.

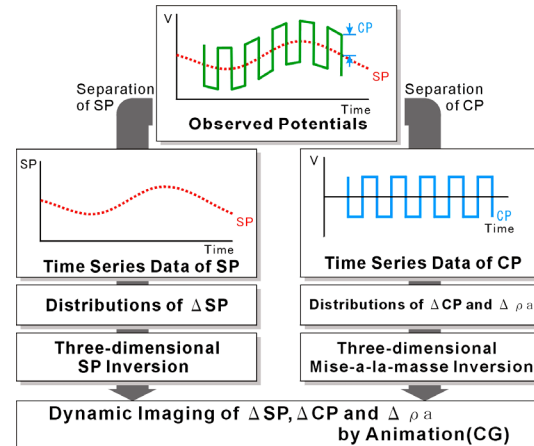


Figure 4. Data processing of FFT method.

In this system, data acquisitions are automatically conducted and time series data are stored on memories of a personal computer with a sampling rate of 1,800 runs/hour. The time series data can be visualized on the CRT of the computer in a real time. Therefore, fluid-flow fronts and the distribution of fluid-flow can be continuously imaged as a function of time on the survey site. Practical images of fluid-flow behaviors may be obtained by making contour maps and bird's-eye views (3-D) with a comparison of two datasets between an arbitrary time lag and an initial time (a base time). These contour maps could be obtained during artificial operations such as hydraulic fracturing, production and reinjection operations.

## RESULTS OF FFT SURVEY

The FFT survey using the S-3 well has been conducted at reinjection site B in the field.

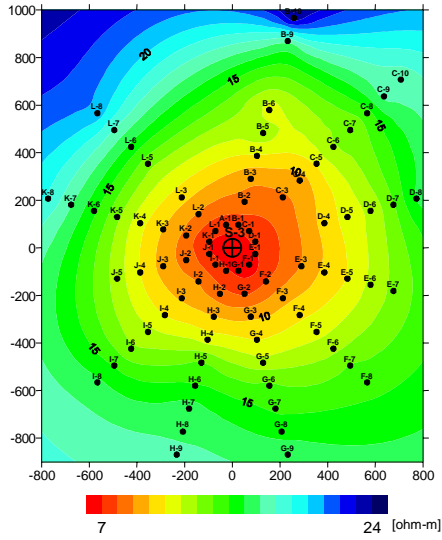


Figure 5. Apparent resistivity distribution.

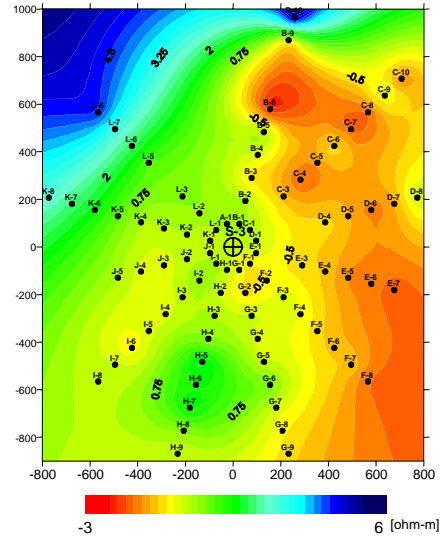
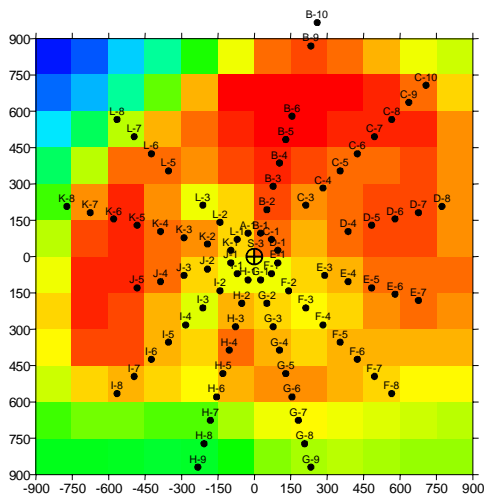
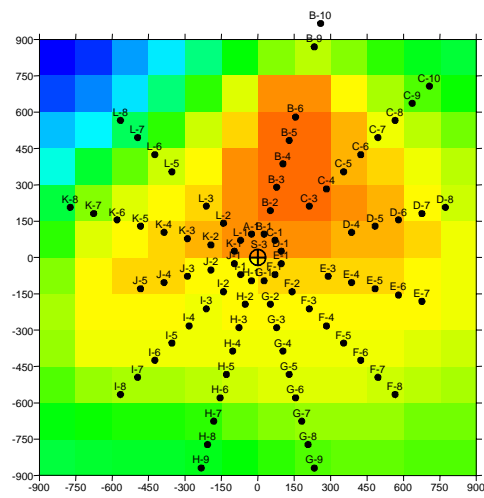


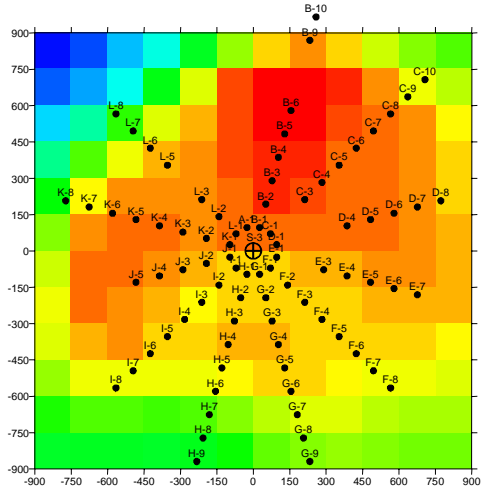
Figure 6. Residual apparent resistivity distribution.



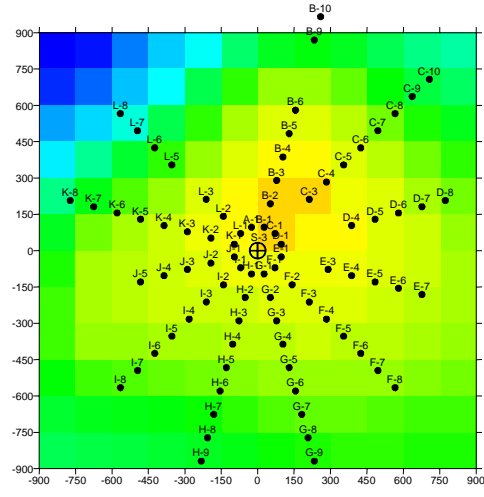
Depth: 0-



Depth 600-



Depth 300-



Depth 900-

Figure 7. Depth sliced contour map derived from 3-D inversion of the Mise-a-la-masse data in the Sumikawa area.

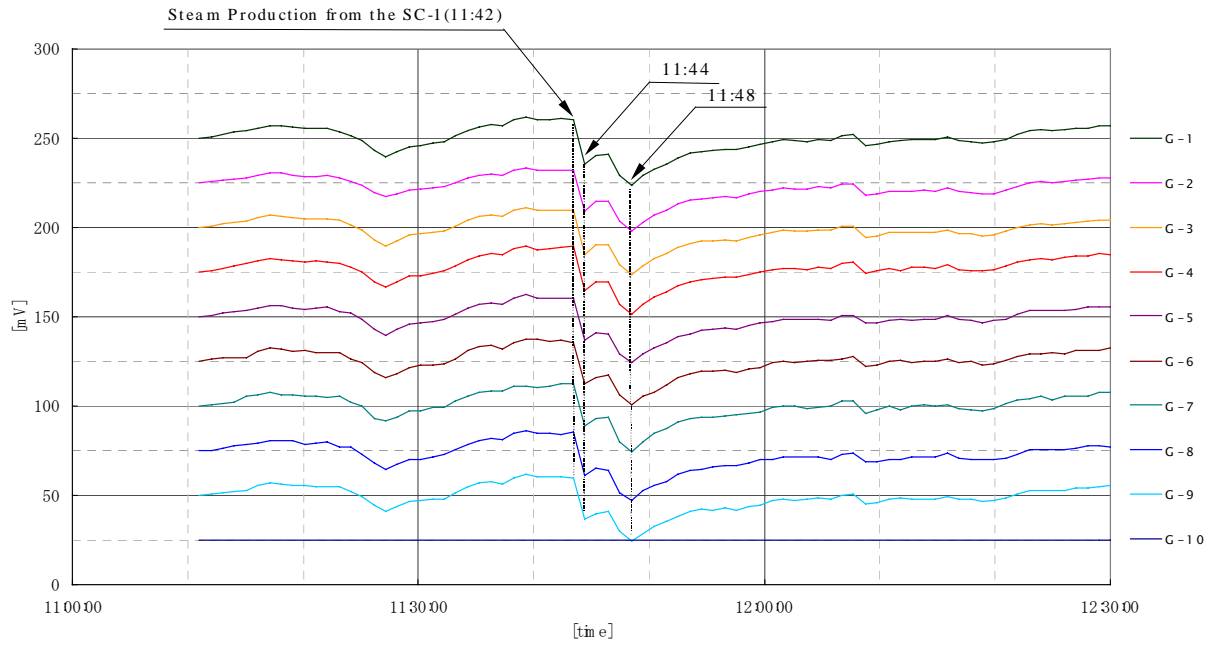


Figure 8. Time series SP data of G-line in the Sumikawa area.

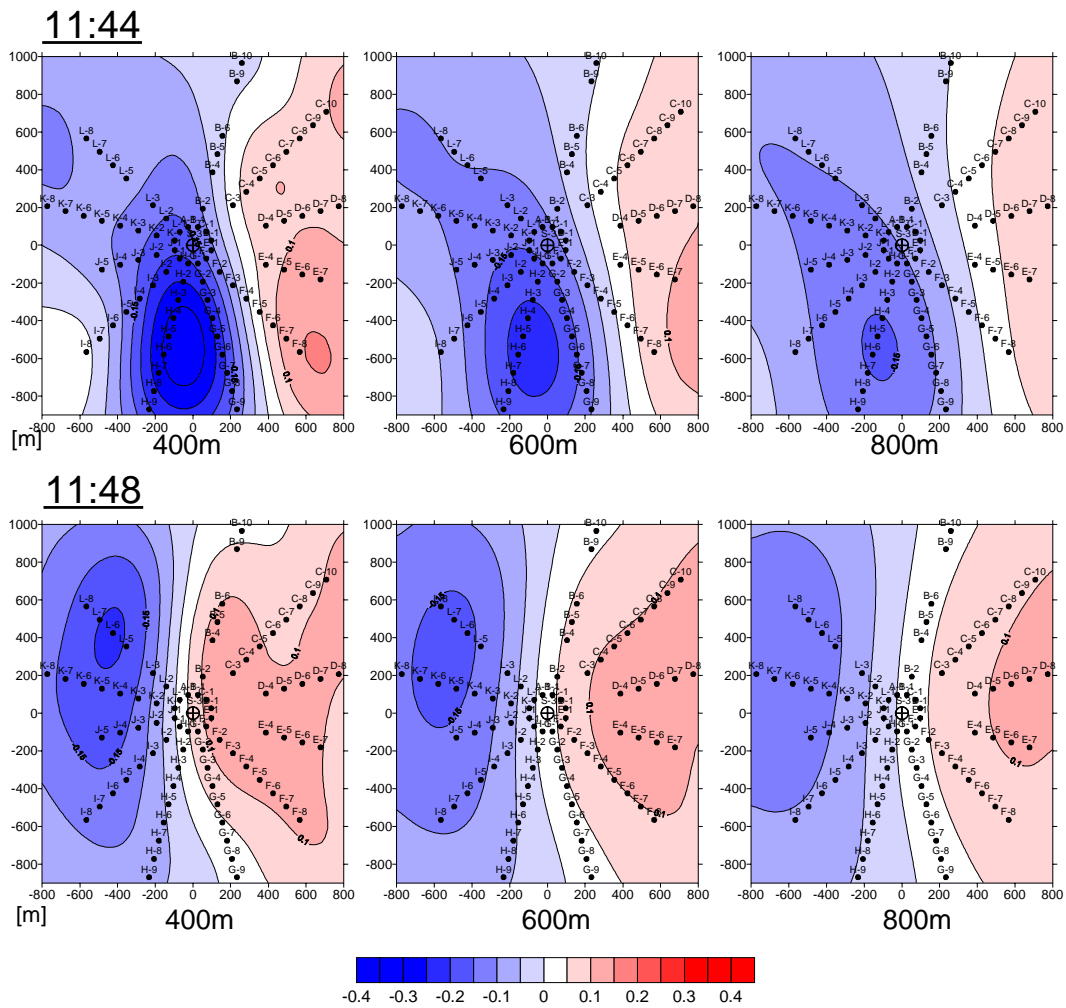


Figure 9. 3-D Inversion of SP data by COP analysis in the Sumikawa area.

The current electrode C1 was connected to the wellhead part of a casing pipe (800 m length) and multiple potential electrodes, 101 are set radially along the survey line from A to L with 100 m interval as shown in Figure 2.

The FFT survey has been conducted for about four weeks from 14<sup>th</sup> September to 7<sup>th</sup> October in 2000 during the periodical inspection of the Sumuikawa geothermal power plant. Data acquisition is automatically conducted, and time-series data are stored on diskettes with a sampling rate of 2 seconds.

### **CHARGED POTENTIAL DATA**

Charged potential data can be obtained by the running average method from observed data. Therefore, the expression for apparent resistivity data can be derived from the charged potential data multiplying by a geometric factor (Ushijima, 1989):

$$\rho = K ( V/I )$$

Apparent resistivity distribution observed on 1<sup>st</sup> October in 2000 is illustrated (Fig. 5).

Figure 5 shows that resistivity distribution of the subsurface is not homogeneous because resistivity changes laterally and vertically as a function of the distance from the well. Therefore, resistivity inversion was applied based on a layered earth model. The result of inversion of the mise-a-la-masse data are as follows: the first layer resistivity and thickness is 2.5  $\Omega\text{m}$  and 800m, the second layer resistivity is 620  $\Omega\text{m}$ . Therefore, residual apparent resistivity values could be calculated using the two-layer earth model. The residual apparent resistivity distribution is shown in Figure 6. It is clearly detected that low resistivity zones are distributed in the eastern area and faults with the strike of north-south direction are delineated in the eastern area from the well.

Finally, 3-D inversion of the mise-a-la-masse data was conducted using a 3-D block model based on the least square method. The resulting depth sliced contour maps are illustrated in Figure 7. Low resistivity zones less than 10  $\Omega\text{m}$  are widely distributed in a shallow depth up to 600 m, but high resistivity zones are distributed in a deeper depth of 600 m.

It is concluded that geothermal reservoir exists beneath the low resistivity zone at the north-east part of the S-3 well in the Sumikawa geothermal field.

### **SELF POTENTIAL DATA**

Self-potential anomalies due to streaming potentials effects have been studied by many researchers since

1936( Mizunaga, et al., 1995). The theory of irreversible thermodynamics in homogeneous 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 anomaly patterns can be visualized investigated by solving the crosscoupled equations for fluid flow and electric current. The anomaly patterns are generally the same over an anomalous body, and it is interesting to note that the location of the maximum (positive) and the minimum (negative) values on appear absolute edges of an anomalous body.

Time series SP of the survey line G are illustrated in Figure 8 during the time range from 11:10 to 12:30 on 1<sup>st</sup> October, 2000. At the instant (11:42) of steam production from the SC-1 well, SP values decrease rapidly and show the minimum value at the time of 11:48 when the amount of reinjection rate increase from C site to D site in the Sumikawa geothermal field as shown in Figure 2. It is concluded that reinjection on the D site affected the SP values drastically.

This transient phenomena of SP can be visualized in detail by calculating SP changes with a function of time using time sliced data.

SP values observed at all stations are decreasing at 2 minutes after the production of the SC-1 well started. Especially, the minimum SP value (-35mV) was observed at the time 11:48. On the other hand, SP values are seemed to increase as a function of time to a steady state condition. However, changes of SP values at each station are not the same order due to the permeability effect. It is noted that SP changes on the south east part (F-line) and east part (D-line) are greater than the western and the other area because of greater permeability.

Therefore, it is concluded that large SP anomalies could be detected due to the dominated fluid-flow in the fractures by the production operation on the C site and reinjection operation on the D site(Figure 2).

### **COP INVERSION OF SP DATA**

A new approach to SP data interpretation for the recognition of a SP source system has been proposed using the charge occurrence probability (COP) function (Patella, 1997).

3-D tomography by COP analysis has been conducted using SP anomaly data observed at 11:44 and 11:48. Depth sliced contour maps of COP analysis are illustrated in Figure 9. It is shown that COP distributions of a negative anomaly indicating a downward flow appear on the site of surrounding the S-3 well and extends to the southern part (H-line). On the other hand, positive SP anomaly indicating upward flow appears on the eastern part such as E-line and F-line.

Therefore, it is predicted that fluid flows from the west part (negative SP anomaly) to east part (positive SP anomaly) by consideration of the origin of streaming potential in the Sumikawa geothermal field.

Especially, it is interesting that positive SP anomalous area detected at the southeast part coincides with the location of production well SC-1 on the C site as shown in Figure 2.

It is noticed that the negative anomaly of COP distributions is moved from south to the northwest part of the S-3 well at later stage (11:48).

It is confirmed that fluid flow behavior can be detected by COP analysis of SP data and the fluid flow diverge from northwest part to east part of the survey lines D and E on the site D as shown in Figure 2.

## **CONCLUSIONS**

A multichannel geoelectrical system and various programs for data acquisition, processing, and interpretation techniques had been developed. The FFT method had been applied to image potential fractures in the Sumikawa geothermal field. The fluid-flow behavior in the subsurface could be monitored and visualized by the present 4-D geoelectrical technique such that: (1) time-series data of charged potentials (apparent resistivities) and self potentials (streaming potentials) could be obtained in real time; (2) fluid-flow boundaries anisotropic permeability can be visualized from the residual potentials obtained by subtracting preinjection data from postinjection data; (3) the anisotropic permeability of the formation can be evaluated from the percent difference of apparent resistivity data based on Archie's law; (4) 3-D distribution of fractures could be imaged by the joint interpretation with the other geophysical data such as MT and VES.

*Acknowledgements: We thank to MMC and MMRC corporations for applying the FFT method to reservoir monitoring in the Sumikawa Geothermal Field, Japan.*

## **REFERENCES**

Ariki, K., Kato, H., Ueda, A., and Bamba, M., (2000), "Characteristics and management of the Sumikawa geothermal reservoir, Japan", *Geothermics*, **29**, 171-189.

Patella, D.,(1977),"Introduction to ground surface self-potential tomography", *Geophysical Prospecting*, **45**, 653-681.

Uchida, T., and Mitsuhashi, Y., (1995), "2-D inversion and interpretation of magnetotelluric data in the Sumikawa geothermal field, Japan", *Report of Geological Survey of Japan*, **282**, 17-49.

Mizunaga,H., et al.,(1995), "Fluid flow monitoring system of a geothermal reservoir by electrical prospecting", *The Memoirs of the Faculty of Engineering, Kyushu University*, Vol.55, No.4, 505-512.

Ushijima, K., Mizunaga, T., and Tanaka, T., (1999), "Reservoir monitoring by a 4-D electrical technique", *The Leading Edge*, Vol.18, No.12, 1422-1424.