Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Imaging of a Geothermal Reservoir using a 4-D Geoelectrical Method

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Keywords: Reservoir geophysics, 4-D geoelectrics

ABSTRACT

An advanced geoelectrical technique for imaging potential fractures has been developed by the Engineering Geophysics Laboratory in Kyushu University. The method, Fluid Flow Tomography (FFT), has been applied to monitor fluid-flow behaviors during water injection and steam production operations in geothermal areas. Distribution and extension of potential fractures can be evaluated by 3-D inversion of induced self-potential (SP) anomalies as a function of time and resistivity structures can be determined by 3-D inversion of the mise-a-la-masse data in a surveyed area. It is concluded that fluid-flow behaviors in potential fractures could be continuously traced and visualized as a function of time by the FFT method.

INTRODUCTION

In order to monitor the transient phenomena of dynamic fluid flow behavior during injection and production operations, we have developed a 4-D geoelectrical system (Ushijima et al., 1999) together with a three-dimensional inversion program for mise-a-la-masse data using a casing pipe as a line source current electrode. This program can be used for interpretation of the mise-a-la-masse data using an arbitrarily shaped casing pipe, such as in directional and horizontal wells. A three-dimensional inversion program of SP data was also developed based on probability tomography. Fluid flow fronts can be visualized from the residual potentials obtained by subtracting the preinjection data from the postinjection data. The amount of fluid-flow and asymmetric anomaly due to anisotropic permeability of the formation, can be estimated from the fluid-flow vectors during massive production and or reinjection operations.

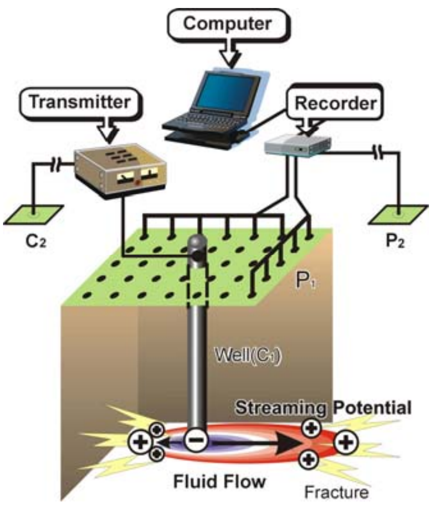

Figure 1: Field layout of FFT measurement.

4-D GEOELECTRICAL METHOD

Figure 1 shows a field layout of a FFT survey. A charged current electrode (C1) is connected to the conductor casing of the well. The earthing electrode (C2) is fixed at 3 km away from the charged well. 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 present FFT survey. An electric current of 1 - 5 A and a frequency of 0.1 Hz are introduced into the earth by a conventional transmitter used for a conventional electrical resistivity surveys. Potential distributions on the ground surface are continuously measured by a digital recording system controlled by a personal computer on the survey site.

DATA PROCESSING OF FFT SURVEY

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 according to the flowchart of data processing as shown in Figure 2.

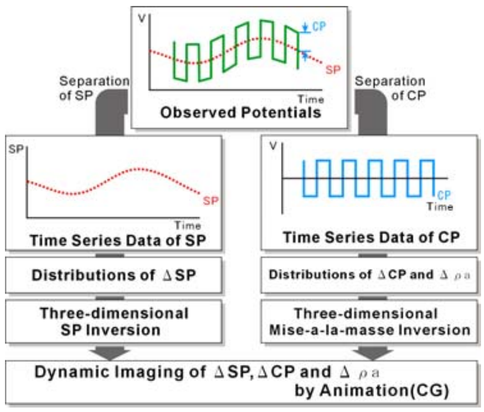

Figure 2: Data processing of FFT method.

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 2 seconds. 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 continuously obtained before and during man-made operations by stimulating reservoirs such as hydraulic fracturing, production and reinjection operations.

3-D INVERSION OF RESISITIVITY DATA

A three-dimensional inversion program for mise-a-la-masse method was developed in order to obtain the three-dimensional resistivity distribution. This program can be used for interpretation of the mise-a-la-masse data using an arbitrarily shaped casing pipe, such as in directional and horizontal wells (Aono et al., 2002).

3-D INVERSION OF SP DATA

Various interpretation techniques have been developed for the interpretation of the self-potential (SP) data. However, a new approach to SP data interpretation for the recognition of a SP source system has been recently proposed using the COP (Charge Occurrence Probability) function (Patella, 1997). We developed a three-dimensional inversion program for SP method based on probability tomography.

SUMIKAWA GEOTHERMAL FIELD

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 the 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.

The Sumikawa geothermal field is located in the Sengan geothermal area, where research in of geology, geochemistry, hydrogeology and geophysics has been conducted by the Geological Survey of Japan and NEDO under the Sunshine Project promoted by the MITI. These studies have shown the tectonics of the Hachimantai region is characterized by block movements and graben structures with a north-south trend as shown in Figure 3. 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 drilling (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 have been obtained by two-dimensional inversion of MT and CSAMT data (Uchida and Mitsuhata, 1995). The resistivity model is characterized by a very low resistivity (1 to 3 Ωm) cap rock beneath a resistive layer and rather high resistivity layer of reservoirs (order 100 Ωm). The very low resistivity of the cap rock is due to clay minerals such as montmorillonite.

RESULTS OF FFT SURVEY

The field survey layout is shown in Figure 4. The FFT survey using the S-3 well has been conducted at reinjection site B in the Sumikawa geothermal field. The current electrode C1 was connected to the wellhead part of a casing pipe (800 m length) and 101 multiple potential electrodes, are set radially along the survey line from A to L with 100 m interval as shown in Figure 4. The FFT survey was conducted for about four weeks from 14th September to 7th October in 2000 during the periodical inspection of the Sumikawa geothermal power plant. Data acquisition was automatically conducted, and time-series data were stored on diskettes with a sampling rate of 2 seconds.

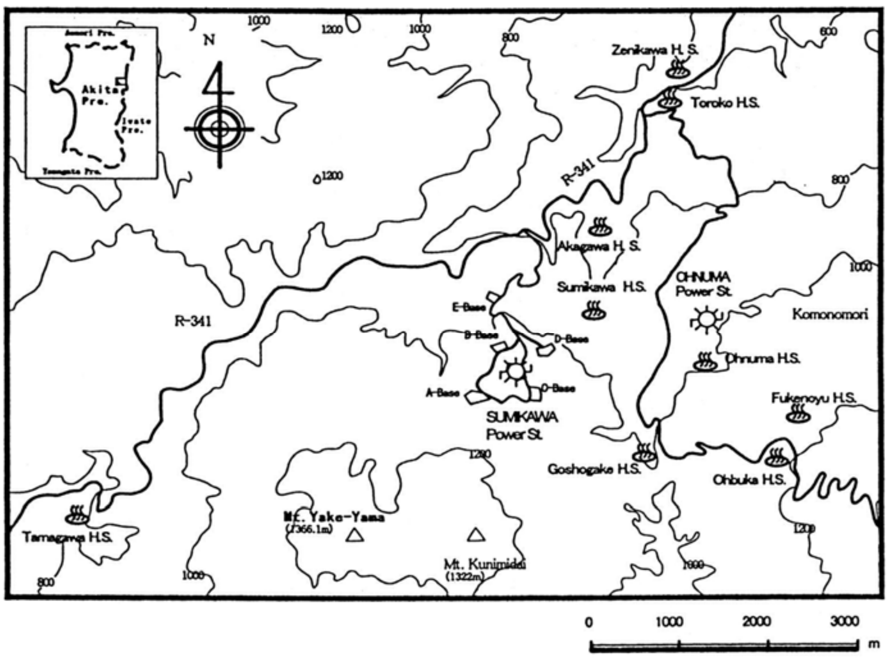

Figure 3: Location map of Sumikawa geothermal field.

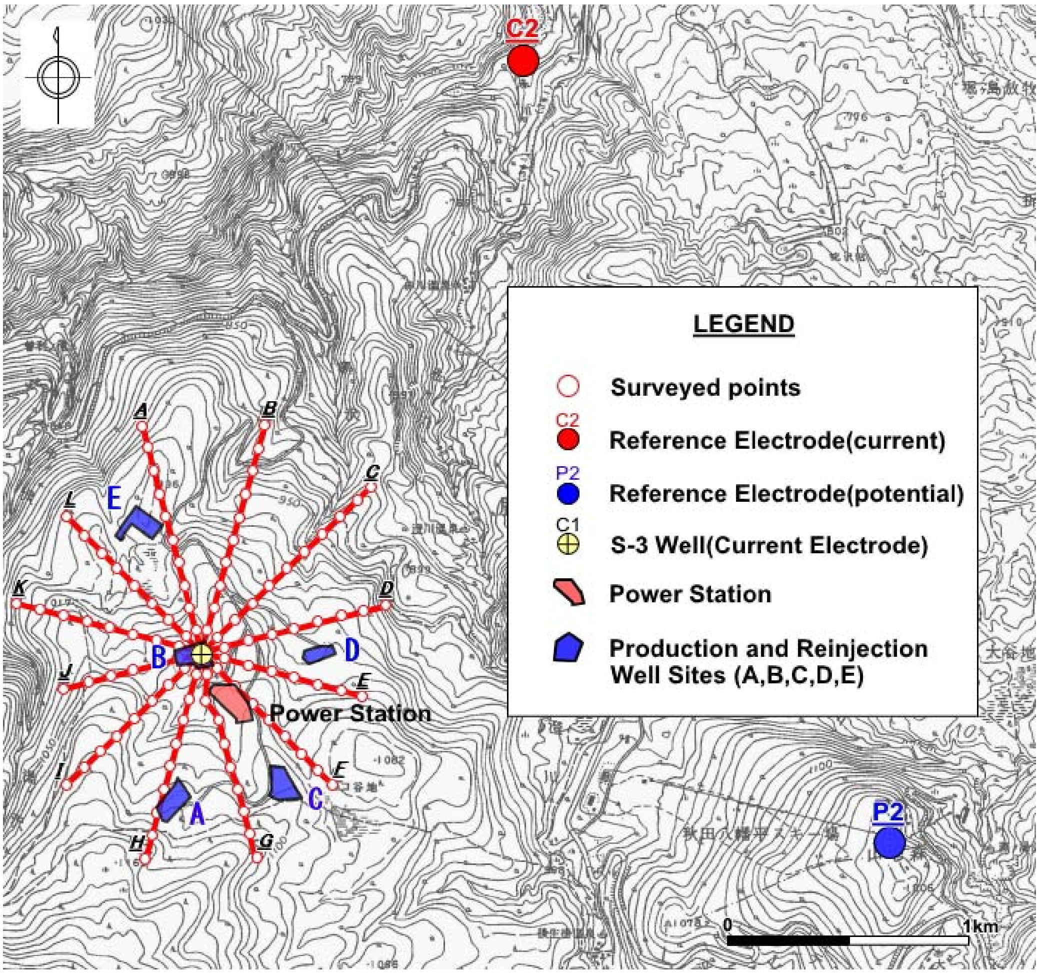

Figure 4: Electrode array of FFT survey in the Sumikawa area.

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). The apparent resistivity distribution observed on 1st October in 2000 is illustrated (Fig. 5).

Figure 5 shows that the resistivity distribution of the subsurface is not homogeneous because resistivity changes laterally and vertically as a function of the distance from the well. The result of inversion of the mise-a-la-masse data are as follows: the first layer resistivity and thickness are 2.5 Ωm and 800m, the second layer resistivity is 620 Ωm. 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 seen that the low resistivity zones are located in the eastern area, and are associated with north-south striking faults.

Finally, a 3-D inversion of the mise-a-la-masse data was conducted using a 3-D block model based on the least squares method. The resulting depth-sliced contour maps are illustrated in Figure 7. Low resistivity zones (less than 10 Ωm) are widely distributed at shallow depths (down to 600 m), while high resistivity zones at deeper depths. It is concluded that the 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 potential effects have been studied by many researchers since 1936. 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 by solving the cross-coupled 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 appear on the absolute edges of an anomalous body.

Time series SP data of the survey line G are illustrated in Figure 8 during the time range from 11:10 to 12:30 on 1st 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 4. It is concluded that reinjection on the D site affected the SP values drastically.

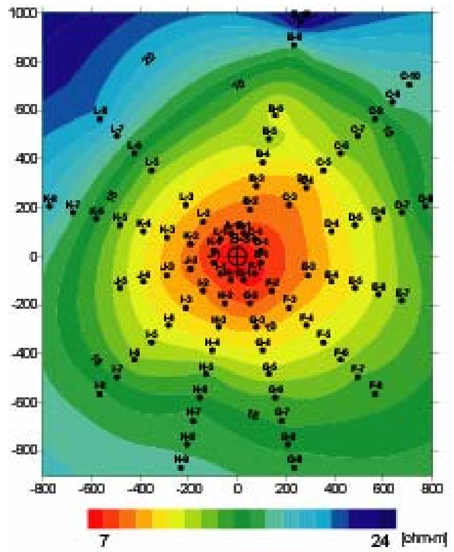

Figure 5: Apparent resistivity distribution.

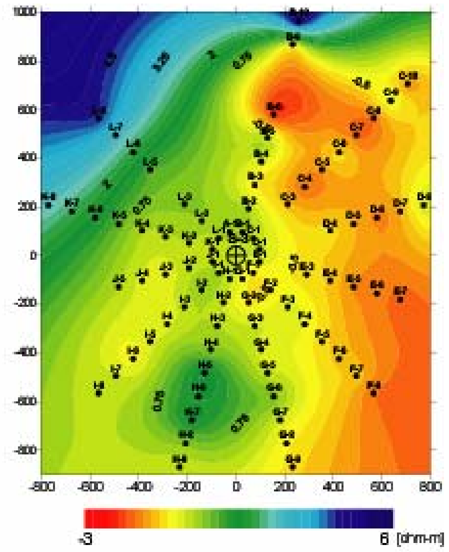

Figure 6: Residual apparent resistivity distribution.

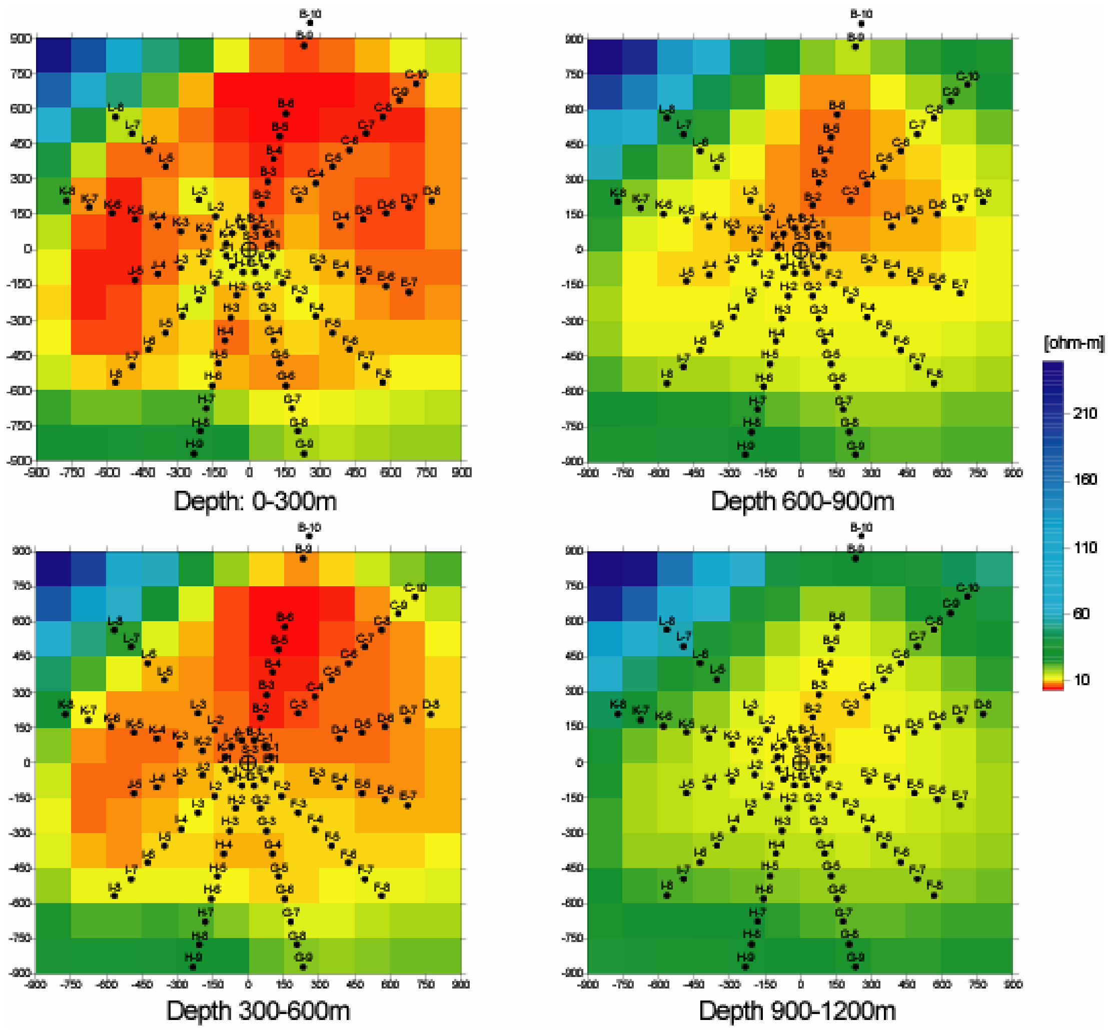

Figure 7: Depth-sliced contour map derived from 3-D inversion of the mise-a-la-masse data in the Sumikawa area.

The transient phenomena of SP can be visualized in detail by calculating SP changes as a function of time using time sliced data. SP values observed at all stations are decreasing 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 seemed to increase as a function of time to a steady state condition. However, changes of SP values at each station are not of 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 dominant fluid-flow in the fractures by the production operation at the C site and reinjection operation at the D site (Figure 4).

COP INVERSION OF SP DATA

3-D tomography by COP analysis has been conducted using the 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 sites surrounding the S-3 well and extends to the southern part (H-line). On the other hand, positive SP anomaly indicating upward flow appears in the eastern part of the area 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). 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 4.

It is noticed that the negative anomaly of COP distributions moved from south to the northwest of the S-3 well at a 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 the northwest part to the east part of the survey lines D and E at the site D as shown in Figure 4.

CONCLUSIONS

A multi-channel 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; and (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.

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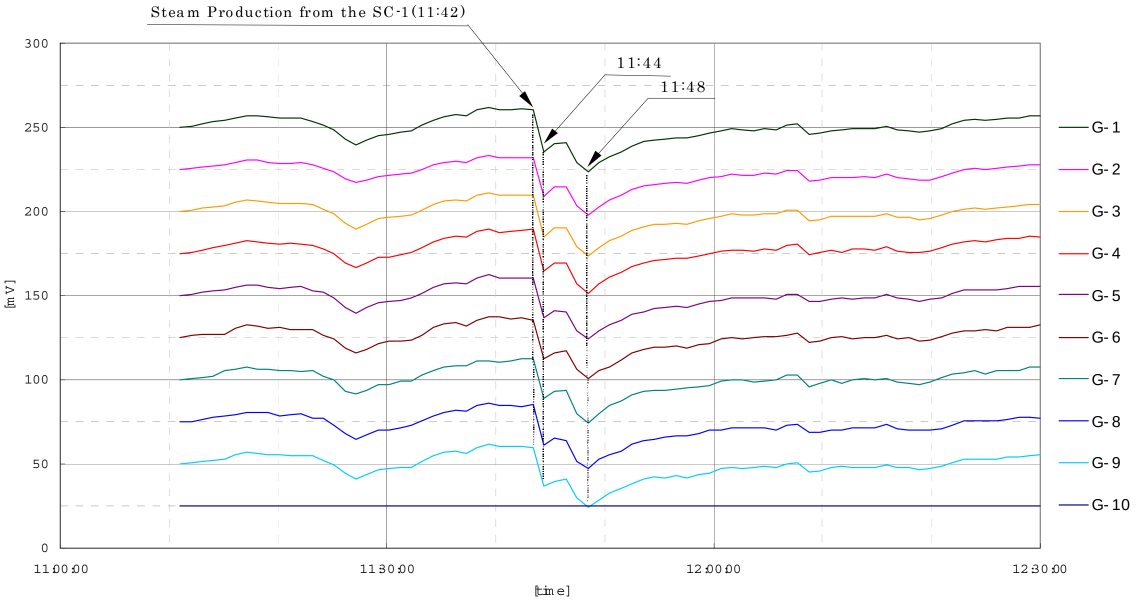

Figure 8: Time series SP data of G-line in the Sumikawa area.

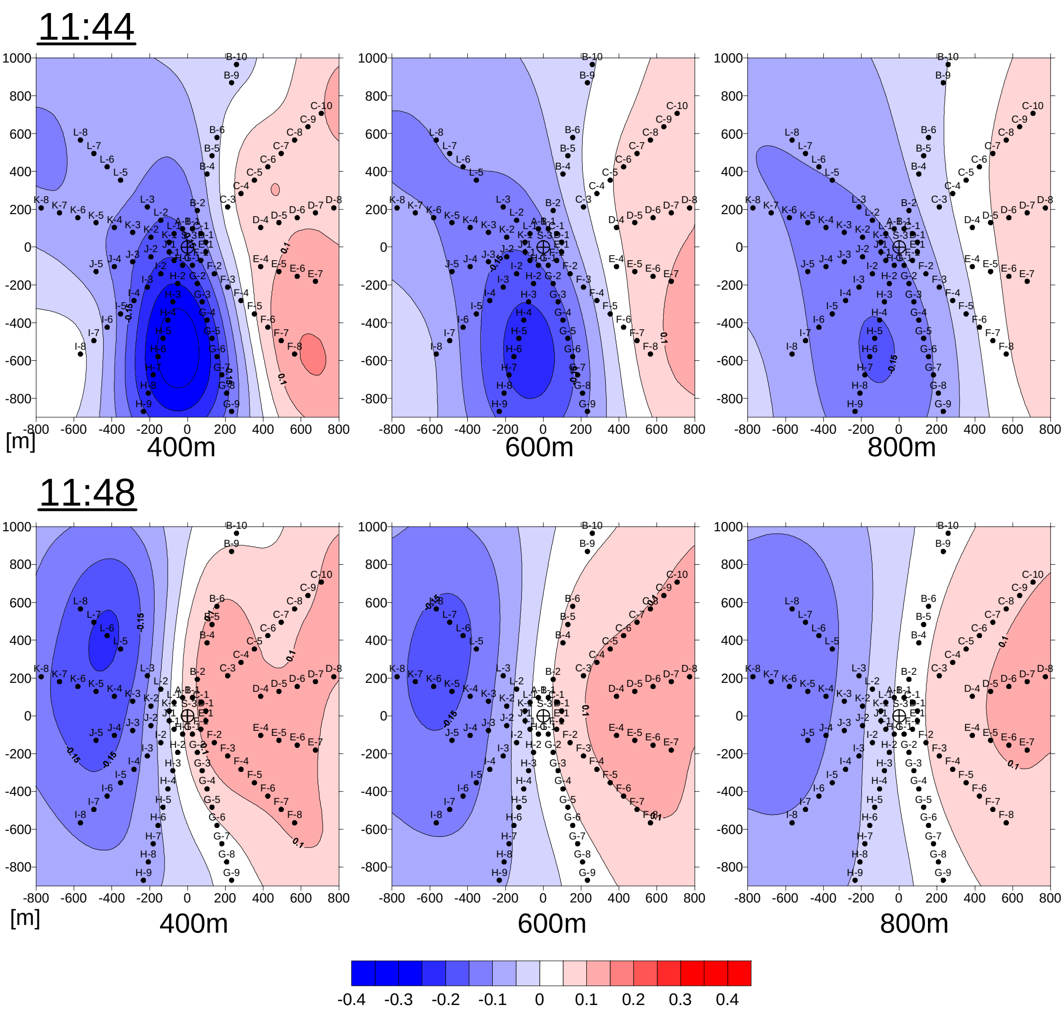

Figure 9: 3-D Inversion of SP data by COP analysis in the Sumikawa area.