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Imaging of Geothermal Fluid Flow by Using Fluid Flow Electromagnetic Method

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ABSTRACT

A new electromagnetic method called the Fluid Flow Electromagnetic (FFEM) method was developed to monitor the behavior of subsurface fluid flow. This method is based on an electromagnetic phenomena induced by subsurface fluid flow. In order to observe an electromagnetic field associated with subsurface fluid flow precisely, a portable triaxial magnetometer was developed to detect the three components of magnetic fields. A dynamic active filter was also developed to reduce electromagnetic noise using switched capacitor low pass filter controlled by a microprocessor. The results of field experiments are shown in this paper.

1. INTRODUCTION

In order to determine the dynamic behavior of subsurface resource fluid (e.g. petroleum and geothermal fluid), it is very important to monitor the three-dimensional dynamic fluid flow in the reservoir using geophysical techniques. A 4-D geoelectrical method called the Fluid Flow Tomography method was developed to visualize the real-time flow behavior of fluid resources in reservoirs. The concept of the Fluid Flow Tomography method is illustrated in Figure 1. This method is a hybrid of the mise-a-la-masse technique and the SP method that was utilized for evaluating subsurface artificial fractures while hydro-fracturing in HDR. It was developed to monitor the fluid flow of heavy oil in oil-sand layers in Canada and to monitor geothermal reservoirs. Electrical phenomena, a streaming potential, and a resistivity change due to fluid flow can be measured using the Fluid Flow Tomography method.

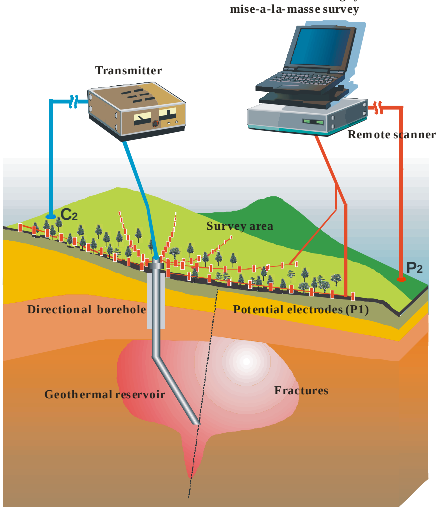

Figure 1: Concept of Fluid Flow Tomography method

However, magnetic phenomena induced by a streaming current are supposed to be observed simultaneously. A new exploration method based on the electromagnetic phenomena induced by subsurface fluid flow was devised to visualize subsurface fluid flow. Figure 2 illustrates the generation of electromagnetic fields induced by subsurface fluid flow.

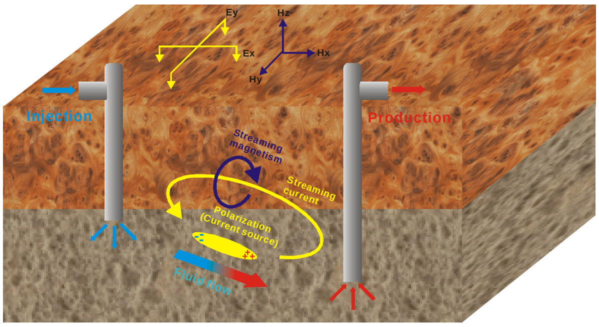

Figure 2: Generation of electromagnetic fields induced by subsurface fluid flow during injection and/or production

2. FLUID FLOW ELECTROMAGNETIC METHOD

A streaming potential associated with fluid flow is known as an electrokinetic phenomena that occurs at the solid-liquid interface between the matrix and water in porous rock. A streaming current is a coupled electric current associated with fluid flow. This current is a local electric current that is proportional to the pressure gradient of the fluid. When a fluid flows in the subsurface and a streaming current is generated, streaming potentials can be observed at the surface. The Fluid Flow Tomography method is a 4-D geoelectrical method for the monitoring of the dynamic behavior of subsurface fluid flow by the spatial distribution and transient change of surface streaming potentials observed simultaneously using multiple potential electrodes at the ground surface.

A large quantity of electric wires extending to the distant electrode from each observational electrode is necessary to carry out observation simultaneously using the conventional Fluid Flow Tomography method. Although it is advantageous to be able to perform observations at the same time using computers after preparation, these measurement preparations are quite time consuming. Therefore, the "Fluid Flow Electromagnetic method" was designed to replace the Fluid Flow Tomography method and overcome this problem. In this new method, two electric fields are measured using two perpendicular dipoles, and three magnetic fields are simultaneously observed using a small triaxial magnetometer. Figure 3 illustrates the concept of Fluid Flow Electromagnetic method.

When a static electric current flows in a conducting wire, a ringed magnetic field occurs in the direction determined by the right hand screw rule, as is formulated in Ampere's law.

In the case of a complicated electric current, a magnetic field occurring around a stationary electric current can be calculated using Biot-Savart's law. If a generated electric current is associated to subsurface fluid flow, a magnetic field should occur in this manner. However, there are a few studies concerning such electromagnetic phenomena. The estimation of direction of fluid flow through streaming current is possible using the subsurface 3-D magnetic field vectors calculated from surface magnetic field.

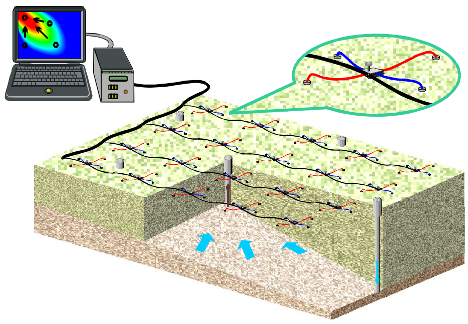

Figure 3: Concept of Fluid Flow Electromagnetic method

3. DEVELOPMENT OF MAGNETOMETER

The simultaneous measurement of the three components of magnetic field at the measurement point is necessary to carry out a Fluid Flow Electromagnetic survey. Induction coils used for MT methods and flux gate magnetometers used for magnetic methods are considered for magnetic field sensors, but they are not suitable for the observation at the many observed points because of their large scale and heavy weight. In order to carry out simultaneous measurement, a small magnetic sensor with high sensitivity is necessary.

When a high-frequency current is impressed into an amorphous wire that has high magnetic permeability, the impedance of the amorphous wire is sensitive to the external magnetic field. This is called the Magneto Impedance effect. The MI sensor is a newly developed magnetic sensor which is based on the Magneto Impedance effect.

Two kinds of magnetometers using MI sensors were developed. One is the triaxial magnetometer used to measure the three components of geomagnetic fields. Another is the triaxial magnetic gradiometer, which measures magnetic gradients of geomagnetic fields. The MI sensor, triaxial magnetometer and triaxial magnetic gradiometer are shown in Figure 4.

4. DEVELOPMENT OF DYNAMIC ACTIVE FILTER

An active noise filter is necessary to precisely measure the transient change of the geomagnetic field associated with subsurface fluid flow in a noisy environment. The active noise filter was developed with the ability to change filter characteristics using software. A diagram of a switched capacitor filter and a dynamic active filter is given in Figure 5. The dynamic active filter consists of three components. The first component is a programmable gain amplifier (PGA) that can control the amplification rate. The second component is microprocessor unit (MPU) that can control the third component, which is a switched capacitor filter (SCF) for noise removal.

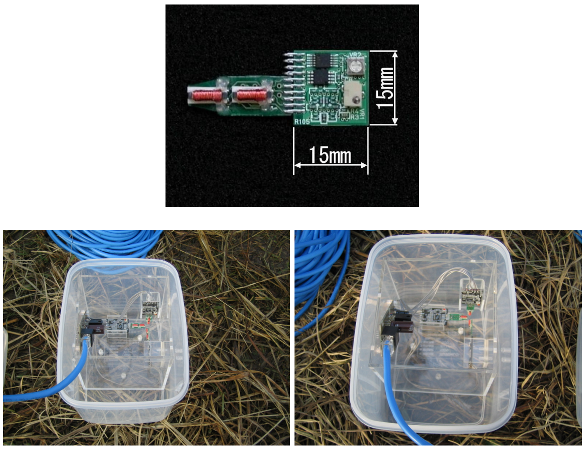

Figure 4: The MI sensor (upper), triaxial magnetometer (right), and triaxial magnetic gradiometer (left)

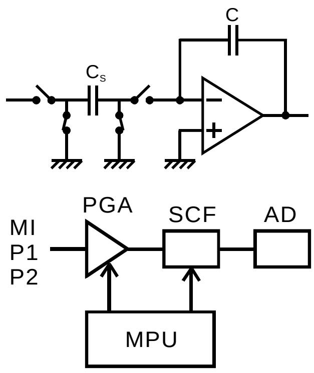

Figure 5: Diagram of a switched capacitor filter (upper) and a dynamic active filter (lower)

Using the dynamic active filter, the output of the MI sensor and the electric sensor can be amplified according to the magnitude of signal. Also, the frequency characteristic of the low pass filter can be changed according to the noise level at the survey field. This structure was adopted to make it possible to change the filter characteristics and use the optimum noise filter. In addition, the cut-off frequency can be changed by monitoring the noise level using a microprocessor, if necessary.

A fundamental experiment was carried out to inspect the performance of the noise reduction filter at the Yamakawa geothermal power plant in Ibusuki, Kagoshima prefecture, Japan in December 2007 using the developed dynamic active filter. The magnetic fields observed on December 14 without using a dynamic active filter are illustrated in Figure 6. Severe electromagnetic noise was observed at the Yamakawa geothermal power station. There is a large-sized dynamo in the power station, and generated electricity is transmitted by power transmission lines. Therefore, an extremely large amount of electromagnetic noise was observed in the neighborhood of the power station.

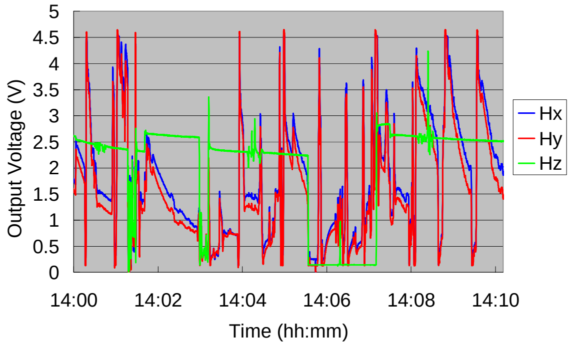

Figure 6: Observed magnetic fields without using dynamic active filter on December 14

The magnetic fields observed on December 21 using a dynamic active filter are shown in Figure 7.

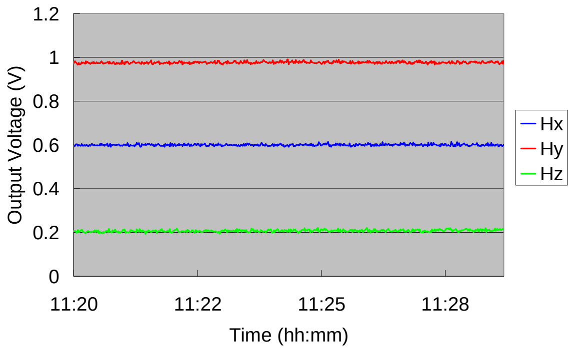

Figure 7: Observed magnetic fields using dynamic active filter on December 21

It was found that noise can be removed using a dynamic active filter, enabling stable data measurement. In this experiment, the cut-off frequency was set to 1 Hz, because the main frequencies of noise source are 60 Hz and their harmonics.

5. FIELD EXPERIMENT

Preliminary field tests were carried out in June 2007 at the yard of the Yamakawa geothermal power plant in Ibusuki, Kagoshima prefecture, Japan to examine the sensitivity of the magnetic field sensor and the noise environment around the measurement area. A picture of the Yamakawa geothermal power plant is shown in Figure 8. In this field experiment, the streaming potential and geomagnetic field were measured using potential electrodes and triaxial magnetic gradiometers, respectively. These measurements were carried out without using the low pass noise filter, which reduced high frequency noise. This experiment was done to determine whether the electromagnetic field associated with subsurface fluid flow could be measured at the time of injection and/or production of geothermal wells.

The measurement was performed with a sampling time of 1 kHz to grasp the frequency of neighboring noises. In this measurement, the noises including 60 Hz and the harmonics were observed. Significant electromagnetic noises of around several 100 mV were included in the raw data before data processing. Because a signal was buried among noises, stacking at an interval of one minute (using every 6,000 data) was performed to reduce the high frequency noise included in the raw data. A picture of the measurement system used in the field experiment is given in Figure 9.

Figure 8: Yamakawa geothermal power plant in Ibusuki, Kagoshima prefecture, Japan

Figure 9: FFEM measurement system used to observe geomagnetic fields

The transient change of the magnetic gradient and streaming potential in the preliminary field measurements are illustrated in Figure 10. In this Figure, Hx, Hy and Hz represent the output voltage of magnetic gradiometers, and dsp6 expresses a streaming potential change at observation point No.6. The sudden change at 10:30 represents the start of injection into well SKG-8, and the greatest change at 12:00 indicates the end of injection. The transient change of the well head pressure in injection well SKG-8 is illustrated in Figure 11. When the well head pressure in the late stages is examined in detail, it can be observed that well head pressure changes in three phases. The magnetic gradient and streaming potential also decrease from their maxima at 12:00 in three phases, reflecting the fact that well head pressure changes in three phases. A large change in streaming potential is predicted such that the fluid pressure distribution in the geothermal reservoir changes suddenly at the beginning and end of injection. In this case, it is considered that the pressure distribution in the geothermal reservoir changes caused by geothermal fluid flow injected then streaming potential and streaming magnetic field were observed thereby. Based on this preliminary experiment, both the electric and magnetic phenomena associated with subsurface fluid flow can be measured simultaneously after processing raw data.

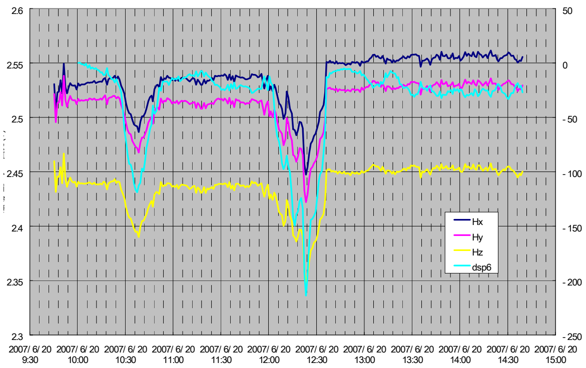

Figure 10: Transient change of output voltage of magnetic sensors (V: left axis) and streaming potential (mV: right axis) observed at point No.6

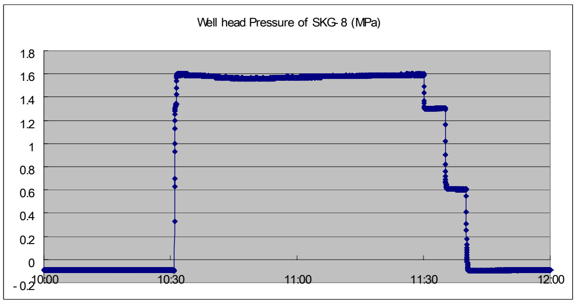

Figure 11: Transient change of well head pressure in injection well SKG-8

A fundamental experiment was carried out to compare the performance of a triaxial magnetometer and a triaxial magnetic gradiometer at the Yamakawa geothermal power plant in December 2007. Using newly developed triaxial magnetometer and triaxial gradiometer that used in preliminary experiment were used in order to compare their performances in this experiment. The dynamic active filter was used to reduce high frequency noise during measurement.

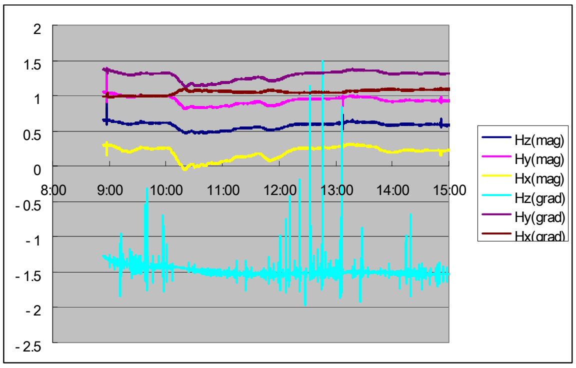

Figure 12: Transient change of magnetic field and magnetic gradient (output voltage of sensor: V) on December 21, 2007

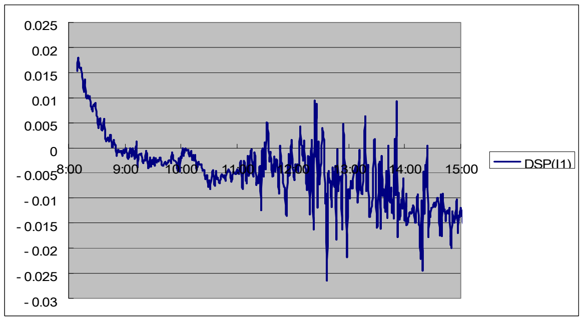

Figure 13: Transient change of streaming potential (V) observed at point No.11

The transient changes of the magnetic field and magnetic gradient near location No.I1 on December 21, 2007 are shown in Figure 12. The transient change of streaming potential observed at location No.I1 is shown in Figure 13. The streaming potential varied began to increase after 10:00 and after 12:30 following periods of decreasing. In addition, a large change with a short period was observed after 11:00. The transient changes in the magnetic field shown in Figure 12 are congruent with the transient changes in streaming potential in Figure 13, except for the z-component of the magnetic gradient. This is because only the z-component of the magnetic gradient was sensitive to the short periodic variation of the streaming potential. The sudden change in magnetic gradient associated with the short period change in streaming potential was observed. Assuming lateral changes in streaming potential at the shallow subsurface around location No.I1, this short period change in streaming potential and the corresponding change in magnetic gradient in the z-direction can be explained qualitatively.

CONCLUSIONS

As a result of this study, the use of the triaxial magnetometer and dynamic active filter which in the Fluid Flow Electromagnetic (FFEM) method was developed. The element technologies of the FFEM measurement system that can measure streaming potential and streaming magnetic field precisely in a terrible noise environment were developed. If a measurement system using the FFEM method is completed by using these element technologies, the dynamic behavior of geothermal fluid in a geothermal reservoir during injection and/or production and the dynamic behavior of petroleum in an oil reservoir during Enhanced Oil Recovery (EOR) can be visualized. In addition to petroleum and geothermal fluid, the FFEM method will be available to monitor the behavior of ground water and CO_2 injected during CCS.

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