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Transient Electromagnetic Survey Using HTS-SQUID Sensor in the Ogiri Geothermal Field, Southwestern Japan

Masato FUKUDA, Toshiyuki TOSHA, Masaki SUGISAKI, Tadaaki SHIMADA and Hidefumi NAKASHIMA

Japan Oil and Gas, Metals national Corporation (JOGMEC), 10-1, Toranomon 2-chome, Minato-ku, Tokyo, Japan

fukuda-masato@jogmec.go.jp (Coresponding auther)

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ABSTRACT

Japan Oil, Gas and Metals National Corporation (JOGMEC) has conducted heli-borne surveys for several geothermal fields in Kyusyu and Tohoku areas to acquire a fundamental geophysical data and to contribute future geothermal development. The survey includes a transient electromagnetic (TEM) method to measure a resistivity structure of those geothermal fields. In order to verify the data quality, we acquired a ground-based TEM data in the survey areas using the equipment with the high-temperature superconducting interference device (HTS-SQUID) magnetometer, which is originally designed and manufactured by JOGMEC to detect mineral resources and is named SQUITEM. There was no precedent for SQUITEM survey in Japanese geothermal field, which is usually located in a mountainous region, and therefore operational impracticability was concerned. The SQUITEM survey was conducted in Ogiri geothermal field not only for obtaining the validation of heli-borne EM data but also for demonstrating the efficiency of the method with the SQUITEM. This paper introduced the SQUITEM survey project around the Ogiri geothermal field.

1. INTRODUCTION

JOGMEC was established in 2004, aiming to secure a stable supply of oil and natural gas, and to ensure a stable supply of nonferrous metal and mineral resources and implementing mine pollution control measures. In 2012, geothermal development and coal development were added in our business as important functions. JOGMEC supports smooth developments of geothermal resources in Japan by providing assistances to geological, geophysical, and well-drilling surveys, equity capital or liability guarantees, and information and data on geothermal resources. In addition to these supports, JOGMEC started R&D programs of geothermal reservoir exploration technique and evaluation & management technique in 2013.

JOGMEC conducts airborne geophysical survey that aims to acquire basic data for evaluations of geothermal resources in order to promote geothermal developments. We apply the airborne (heli-borne) gravity gradiometory (AGG) and TEM survey and acquire detailed gravity gradients and resistivity structures in several geothermal fields, though there was no record of these survey methods in Japan. Heli-borne TEM is a time-domain (or transient) electromagnetic survey method with helicopter and is expected to acquire the extensive resistivity structure effectively. Since this method was the first application in Japan, we had a plan to conduct a ground TEM survey in order to evaluate the heli-borne TEM data within the survey area.

JOGMEC developed a TEM survey system using High-Temperature SQUID magnetometer, which was named SQUITEM. This measurement system showed superiority in depth compared with the conventional TEM survey by using an induction coil receiver (Arai et al., 2005). In order to acquire the resistivity structure to adequate depth range, we applied the SQUITEM to the validation of the heli-borne survey. The Ogiri geothermal field is located in Kirishima heli-borne TEM survey project area. The resistivity structure was well examined by the previous CSAMT and MT surveys. The SQUITEM survey lines were designed to locate on a part of the previous survey lines. This survey design is capable of comparing the SQUITEM data to not only the heli-borne TEM data but also CSAMT and MT data. There was no precedent for SQUITEM survey in Japanese geothermal field, which is usually located in a mountainous region. Therefore, operational impracticability was concerned. We conducted SQUITEM survey in the Ogiri geothermal field to demonstrate the efficiency of this method as well as to validate the heli-borne EM data. .

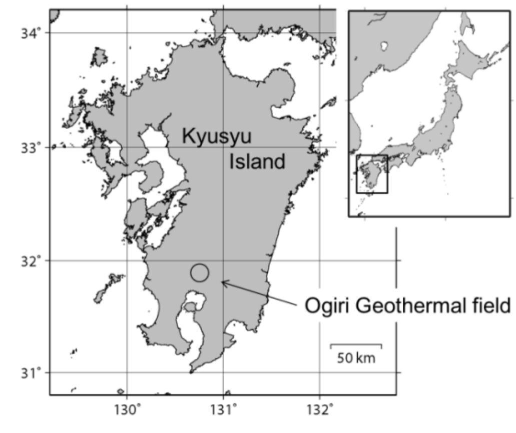

Figure 1: Location of the Ogiri geothermal field.

2. OGIRI GEOTHERMAL FIELD

2.1 Geological setting

The Ogiri geothermal field is located at the foot of Kirishima volcanic zone on the volcanic front formed by the Philippines sea plate subduction into the Eurasia plate. The basement of the Ogiri field is the Cretaceous-Paleogene Shimanto Group. Boring exploration results showed that the Shimanto Group is depressed around the Ogiri field and is covered by the Quaternary volcanic rocks and lacustrine deposits. Faults and lineaments have dominant strikes of NW-SE and ENE-WSW in this field and hot springs, fumaroles. The geothermal altered zones are aligned along this direction. In Ogiri field, three major faults are formed in the Quaternary formation, which is named as Sakkogawa, Ginyu and Shiramizugoe (from north to south) faults. The major target faults for geothermal development are Ginyu and Shiramizugoe faults. The cap rocks consist of hydrothermal altered minerals such as smectite, which are formed at the depth between 200 m and 500 m, and separate the shallow subsurface ground water and deep geothermal fluids. A productive geothermal reservoir is formed in the Pleistocene formations under the cap rocks. (Goko, 2004).

2.2 Ogiri geothermal power plant

The Ogiri geothermal field lies to the west of the Kirishima volcanic zone, in southern Kyushu island, Japan. The Ogiri geothermal power plant started the operation in 1996 with an installed capacity of 30 MWe. Main production zone is a typical fractured reservoir formed along the Ginyu fault accompanied by a fumarolic zone. There are fourteen production wells and seven injection wells with depths between 987 m and 3,097 m and between 808 m and 1,598 m, respectively. A reported production rate is 252 t/h of steam and 958 t/h of hot water in March, 2012. (Therm. Nuclear Power Eng. Soc., 2012).

2.3 Prior survey review

Nittetsu Mining Co., Ltd, the developer of the Ogiri geothermal field, started exploration around the Ginyu and Shiramizugoe areas in 1973, and a total of twenty-one exploration wells were drilled until 1984. Those drilling exploration showed that Shiramizugoe was prospective and Ginyu area had a potential to develop (Goko, 1995). The Ogiri field was chosen as a test field for two R&D projects conducted by New Energy and Industrial Technology Development Organization (NEDO), governmental agency. In 1995, NEDO conducted a research to develop an accurate technique to explore a fracture reservoir, which predominates the geothermal fluid flow. In this research, various techniques utilizing an elastic wave such as reflection seismic survey were applied to around Ogiri field. In the aftermath, NEDO started another research project in 1997 and approached to develop the monitoring technique for the fluctuation of reservoir by using electric and electromagnetic measurements. In this project, SP (self potential) and MT monitoring techniques were developed and electromagnetic measurements with a close measurement distance of about 100 m (Horikoshi et al., 2005). In 2013, JOGMEC applied heli-borne gravity gradiometory survey to Kirishima area including the Ogiri field, and acquired data related to the subsurface structure around this field.

2.4 Heli-borne TEM survey

In Japan, most geothermal resources are distributed in mountainous areas, which are difficult to access and also are located in natural parks. Nearly 80% of the geothermal resources are presumed to exist in the natural parks. Airborne geophysical survey is an effective method to acquire data from wide area without modification of the land surface and also an useful technique to explore Japanese geothermal fields. JOGMEC conducted a heli-borne time domain electromagnetic survey to provide an extensive resistivity structure around geothermal fields used as fundamental data for domestic geothermal exploration projects.

Figure2: Heli-borne TEM survey (http://www.cgg.com/).

The heli-borne TEM survey was operated by CGG Aviation (Australia) Pty Ltd. The specification is shown in Table 1. The transmitter loop size had a diameter of 30 m, and the dipole moment was about 1×10^{6} Am^2. These specifications were optimized in consideration of the exploratory environment such as the terrain condition and the operating temperatures. In this survey, the helicopter flied at one hundred meters altitude with towing the transmitter loop about fifty meters below the air flame. The loop altitude would be, however, changed, depending on landscape issues or ground installations.

Table 1: Specifications of the HELITEM system.

Transmitter	
Loop size	**30 m across**
Base Frequency	**25 or 30 Hz**
Time gates	**30 channels**
Dipole moment	**1.2 x 10^6 A· m^2 (@+1℃)** **1.0 x 10^6 A· m^2 (@+20℃)**
Pulse width	**3.7 ms**
Receiver	
EM Receiver	**3-component X, Y and Z induction coil sensors**
Sampling rate	**10 Hz**
Sensitivity	**0.01nT**

We estimated the penetration depth of the heli-borne TEM survey based on the specifications. Skin depth is generally defined as the distance in which a plane wave decreases to 37% of its initial amplitude. In the TEM case, it can be expressed by the following equation (Spies, 1989; Nabighian and Macnae, 1989);

$$\delta = \sqrt{\frac{2t}{\sigma\mu_0}} \quad (1)$$

where t, σ,μ_0 are the ending time of primary pulse, the conductivity and the permeability of free space, respectively. In the assessment, the estimations of the effective skin depth were conservatively de-rated by being set to 0.55δ based on the contractor's experiences. Additionally, the skin depths were only calculated for times when the secondary response was above the noise specification of 5nT/s. The modeling results are shown in Table 2. In case of the loop altitude of 60 to 80 m, the depth of exploration was expected to be over 400m for the resistive ground conductivities and less than 300m for the conductive ground conductivities. The distribution at the top of the low-resistive cap layer was obtained below the shallow zones in which the geothermal resources were expected to develop. The distribution map would address the concentration of the area for the intensive investigation of geothermal resources. This was the first operation of the time domain heli-borne TEM survey in Japan. Therefore, we started the survey at the developed area where the geological understanding has grown.

Table 2: The results of skin depth modeling for several transmitter loop altitudes.

Loop altitude	10Ωm half space	50Ωm half space	100Ωm half space
60m	**244m**	**375m**	**441m**
80m	**238m**	**368m**	**430m**
100m	**232m**	**362m**	**430m**
120m	**226m**	**355m**	**419m**
152m	**215m**	**341m**	**407m**

3. SQUITEM SURVEY PROJGECT

3.1 SQUITEM

JOGMEC developed a TEM survey system using High-Temperature SQUID magnetometer to intensify the exploration depth of TEM measurement (Arai et al., 2002; 2005). An induction coil receiver, which is commonly used for TEM measurements, measured a time-derivative magnetic field. In principle, an electro motive force is measured as a large value when the magnetic field changes rapidly. If the changing rate of the magnetic field is slower, measured electromotive force becomes smaller, implying that such a situation is an adverse for the conventional induced coil receiver measurement in observational aspect. The magnetic field was observed as the low time decay against low resistivity zone.

Arai et al. (2008) discussed the efficacy of the direct measurement of magnetic field by showing the modeling results of the different responses between the magnetic field and the time derivative of the magnetic field for the situation that the conductive surface layer covered the target zone of a mineral deposit. Calculated responses for the magnetic field (B) and the time-derivative magnetic field (dB/dt) is shown in Figure 3 (b) and (c), respectively, based on a resistivity structure model shown in Figure 3 (a). Horizontal and vertical axes show the elapsed time after the transmission electric current was shut off and the electromagnetic responses, respectively. Black lines indicate the calculation in the case where the bottom layer does not exist. Comparison of the elapsed time of the separation of the black and red lines between (b) and (c) shows that the magnetic field response at the top of the third lowest resistivity layer appeared earlier than the time-derivative of the magnetic field. The response at the top of the third layer at the depth of 600m was expected to be stronger than the SQUITEM system noise level. However, the response of the time-derivative of the magnetic field appeared bellow the conventional TEM system noise. This modeling result showed the efficacy of measuring the magnetic field directly.

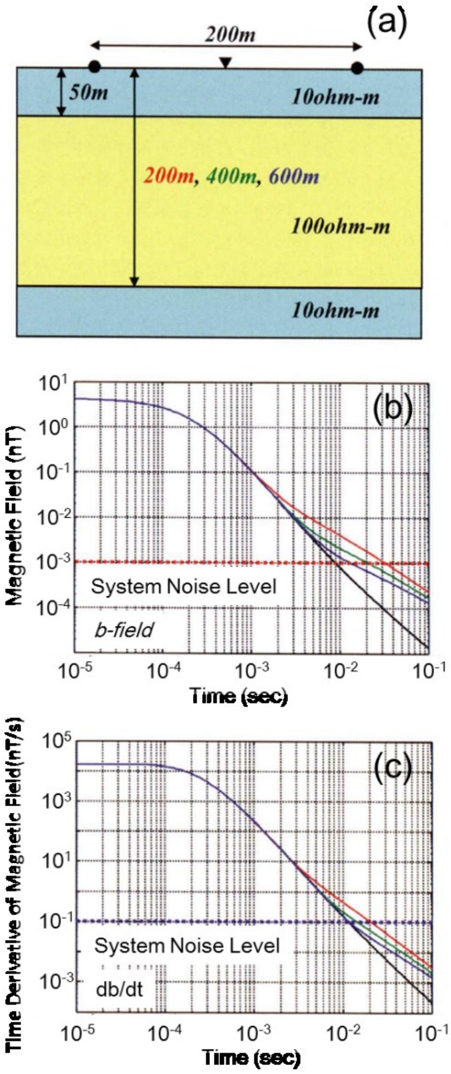

Figure 3: Comparison of the time decay of the magnetic field and the time derivative of the magnetic field based on resistivity structure model. (a)Three-layered resistivity model. Black dots on the surface show the transmitting loop location, and the triangle shows the receiver location where the time decay of the magnetic field and the time derivative of the magnetic field were calculated. (b) Responses of Magnetic field, and (c) Time derivative of the magnetic field. The red, yellow, green and black lines show the calculated responses with changing the depth of third layer from 200m, 400m, 600m and the case of non-existing third layer, respectively. The horizontal red dotted line shows the each sensor system noise levels (after Arai et al., 2008). The noise level of (b) refers to the former version of SQUITEM (SQUITEM-2).

In 2006, JOGMEC applied the SQUITEM to a metal exploration in Australia and found low resistivity distribution that the conventional TEM survey failed to detect it accurately. The low resistivity anomaly was verified with the concentrated sulfide minerals by boring exploration (Arai et al., 2008).

The SQUITEM was improved in the measurement accuracy and the portability. We applied the latest version named SQUITEM-3, which is shown in Figure 4. SQUITEM-3 measured a vertical component of magnetic field with a sampling rate of 100 kHz and the noise level was estimated to be 30 fT/Hz (Hato et al., 2013). Sugisaki et al. (2013) compared the measurable depth between the SQUITEM-3 magnetometer and the conventional fluxgate magnetometer and concluded that the SQUITEM-3 had 1.2 times of the depth detection capability of fluxgate magnetometer.

Figure 4: SQUITEM-3 magnetometer (left) and receiver system (right) (Sugisaki et al., 2013)

There were few TEM systems using the SQUID magnetometer, such as LANDTEM and DEEP HTS developed by CSIRO and Supracon respectively. Information shortage of the LANDTEM and the disunity of each specification items do not allow us to compare simply. The field noise was one of the comparable specifications that were available on their brochures and the level of LANDTEM and DEEP HTS are 350fT/Hz$^{1/2}$ and 50fT/Hz$^{1/2}$ respectively (Supracon; CISRO). The noise level of SQUITEM-3 was 30 fT/Hz$^{1/2}$ and it had an advantage over those in other equipment. However, it was not entirely correct to compare naively with specifications until we acquire the data by using those systems at the same field.

3.2 SQUITEM Survey Area

SQUITEM survey lines were designed to locate on a part of the previous CSAMT and MT survey lines. This survey design enabled to compare not only the heli-borne TEM data but also existing CSAMT and MT data (Figure 5). We applied a moving loop with 100×100m for transmission. Measurement location intervals were based on 100m and varied depending on the purpose of the measurement.

We estimated the response of the low resistive cap rock layer with 1-D modeling which was the same method used in Figure 3(a) (Arai et al., 2008), on a trial basis. We made the three layer resistivity structure model in the Ogiri geothermal field by reference to the previous models (e.g., Uchida, 2005; NEDO, 1999). The layers were corresponded to a covering layer (100 ohm-m), a cap rock layer (3 ohm-m) and a reservoir (30 ohm-m) from the top to the bottom. In this modeling, we assumed the thickness of the cap rock layer as 300m. We calculated the magnetic field at the surface by changing the thickness of the top layer from 0 to 1000m, and confirmed that the SQUITEM-3 is able to detect the top of the cap rock layer underlying shallower than 500m, based on the noise level of past records.

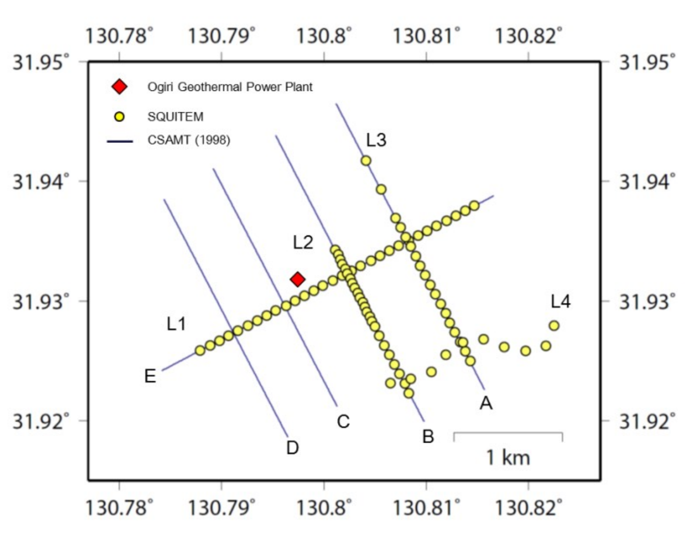

Figure 5: SQUITEM Survey Area: Red square shows the location of the Ogiri geothermal power plant. Yellow circles show the SQUITEM survey locations. Five blue lines show the prior CSAMT survey lines and the place where the joint inversion was conducted with MT data.

CONCLUSIVE REMARKS

The SQUITEM data analysis and the heli-borne TEM survey has been in operation. Comprehensive evaluation will be completed by March, 2015. It is expected that the SQUITEM and the heli-borne survey results show the consistency with resistivity structure estimated by prior electromagnetic survey such as CSAMT and AMT. The principal measurement of the SQUITEM is the same as that of the heli-borne TEM. Therefore, the consistency of the results analyzed by those two measurements would guarantee the quality of the extensive resistivity structure acquired by the helicopter.

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