DEVELOPMENT OF EFFICIENT AND HIGH-RESOLUTION TEM METHOD FOR GEOTHERMAL EXPLORATION

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ABSTRACT

For the purpose of surveying geothermal resources, electromagnetic (EM) methods such as magnetotelluric (MT) and controlled-source audio-frequency MT (CSAMT) are widely used. However, the MT and CSAMT are disadvantaged in terms of a measurement efficiency in geothermal fields particularly located on mountainous areas such as Japanese geothermal fields, and in deep investigation, respectively. Therefore, JOGMEC has developed a SQUITEM system which is both high measurement efficiency and high resolution from shallow to deep section. The SQUITEM is a transient-EM (TEM) method using a super-conducting quantum interference device (SQUID) which is a high sensitivity magnetometer that has a wide bandwidth, a high dynamic range and offers high field sensitivity even at low frequency. SQUITEM was originally developed in order to investigate resistivity structures of shallow section for metal exploration. JOGMEC geothermal team focused on its high measurement efficiency and its high resolution, and considered whether it can be used for geothermal exploration. As a result of a field test of the original SQUITEM at Ogiri geothermal field in Kagoshima prefecture of Japan, we found that its measurement efficiency was good; however, its investigation depth was insufficient for geothermal explorations. Therefore, we constructed a new SQUITEM system for deep exploration more than 2 km depth. We tested the new SQUITEM system at the field near Yamagawa geothermal field in Kagoshima. By comparing with a previous MT survey at the same fields, we could show that the investigation depth of our new system was near 3 km. Moreover, since the investigation time is relatively short and therefore its cost is relatively low, we expect that our SQUITEM system can be a standard tool for geothermal exploration.

1. INTRODUCTION

Since the Fukushima nuclear accident in March 2011, the Japanese government has been promoting renewable energy alternatives such as geothermal energy, and has set a goal to raise geothermal power generation output to three times the current level (520MW) by 2030. In order to accomplish the government goal, JOGMEC which assumes respective roles as an incorporated administrative agency provides a wide range of support which includes subsidies for geological surveys such as surface exploration, drilling survey, etc., investment and debt guarantees, R & D and collection and provision of information.

As part of the R & D regarding geothermal exploration, in order to further promote exploration activity by municipality and private company, the JOGMEC geothermal team has been working on developing the EM method which is a lower cost than conventional methods and has a high resolution even in deep section. Since Japanese geothermal potential fields are located on mountainous areas, the burden of investigation preparations is large and thus the preparation time tends to become longer, namely the investigation cost tends to be expensive. Hence, the exploration methods that total investigation time is short are desired.

We focused on the SQUITEM which has been conventionally used in shallow surveys with the high field sensitivity and the high measurement efficiency and considered whether the SQUITEM can be used for geothermal exploration. This paper introduces our new exploration system and the results of field tests.

2. GEOTHERMAL EXPLORATIONS

Geothermal resources are said to be composed of three structures: heat, reservoir and geothermal fluids flow. The main objective in geothermal survey is to understand the structures of the geothermal system composed of these factors. Although there are various survey methods, the EM explorations which investigate the resistivity structures have played a central role in geothermal surveys since they can estimate the underground resistivity structures which are strongly related to the geothermal fluid activities.

One of the target in the EM explorations is to investigate a spread of a cap-rock which keeps the geothermal fluid in the underground. The cap-rock is often a layer containing a lot of high swellabillity clay minerals such as smectite and has a high conductivity than surrounding rocks. Therefore, the EM explorations are possible to indirectly know the areas where the geothermal fluids exist. The other target is to detect the fracture zones which provide storage space for the geothermal fluid. The fracture zones have high porosity and stores the geothermal fluid, therefore, the fracture zones show the low resistivity, but it is generally rare that the fracture zones can be detected directly. However, since the fracture zones often grow around intrusive rocks which show higher resistivity than the surrounding rocks due to their low porosity and high dense, it is possible to detect the potential areas where the fracture zones may grow. Moreover, if the resistivity transition zones are detected by the EM explorations, there is a possibility of faults and fractures zone.

3. EM METHODS FOR GEOTHERMAL EXPLORATION

In geothermal explorations, the MT and CSAMT are widely used. Fig. 1 shows a schematic image of these measurements. First, the MT is a passive geophysical method which measures natural time variation of the Earth's magnetic and electric fields (B-field and E-field, respectively). By measuring them and calculating the ratio of the electric and magnetic variations can be used to invert for a subsurface resistivity structures. The MT has an advantage in investigation depth, which can be more than hundreds of kilometers by measuring low frequency data. However, it takes a long time (usually more than 1 night) to measure the B- and E-fields responses since the source is natural signals and the signal can be always unexpected. Moreover, although the MT can conduct a multipoint measurement, the apparatuses such as coils are heavy such that the preparation for the measurement is quite hard and requires a lot of workers particularly in mountainous areas.

On the other hand, the CSAMT is similar to the MT with the exception that it uses an artificial source. Electrical currents with various frequencies are injected into the ground away from the target area by a transmitter using a grounded wire. By using the artificial source, the investigation time becomes much shorter than that of the MT method. However, since lower frequency signals cannot be used for its analysis due to a near field effect, the investigation depth is usually less than 1 km.

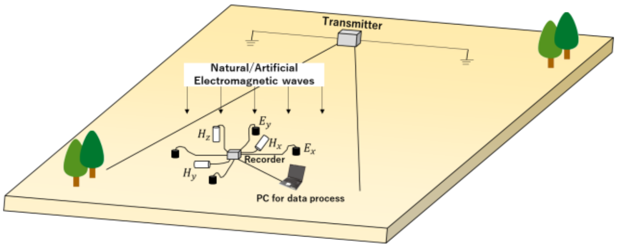

Figure 1: The schematic image of the MT and CSAMT measurements.

4. SQUITEM

Although the MT and CSAMT are widely used in geothermal explorations, the exploration method with further measurement efficiency and the high sensitivity for deep exploration is desired for more promoting the geothermal survey. Therefore, we focused on the TEM system using the SQUID which is a high-sensitivity magnetometer.

4.1 TEM Method

The TEM method is the EM method measuring in a time domain, unlike the MT and CSAMT which measure in a frequency domain. Once a current flowing in a transmitter loop is turned off abruptly, the collapsing EM field induces eddy currents in the underground according to Maxwell's equation. These eddy currents produce secondary B-fields, whose propagation depends on the conductivity distribution in the subsurface (Fig. 2). Unlike the frequency domain EM, the TEM is not affected by the primary B-field which is not related to the underground resistivity structure since it measures only the secondary B-fields. Therefore, the TEM has the advantage that it can easily improve the signal to noise ratio by increasing the transmission moment.

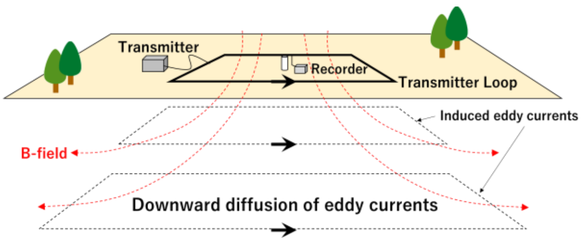

Figure 2: Propagation of eddy currents in underground.

4.2. Conventional SQUITEM System

Fig. 3 shows a configuration of the conventional SQUITEM system developed by JOGMEC metal team and mainly used in shallow mineral exploration. Fig. 4 also shows pictures of both SQUID sensor and a dewar vessel containing it with a recording system which can real time monitor the B-field responses. The SQUID magnetometer is a high sensitive sensor than the induction coil sensors which are used in the conventional TEM. According to Hato et al. (2013), a noise level of the SQUID is 30 fT/Hz$^{1/2}$ at 1 kHz, which is lower than that of the other sensors. Moreover, SQUID's bandwidth is from DC to 10 kHz and its dynamic range is 100 dB, where are superior to the other sensors. As a result, the investigation depth of the TEM using the SQUID is deeper than that of the TEM using the other sensors. Further, according to Arai et al. (2008), the investigation depth is deeper when measuring the B-field directly than measuring the time derivative of the B-field (dB/dt). This also supports that the investigation depth of the SQUID which measures B-field responses is deeper than that of the induction coils which measure dB/dt.

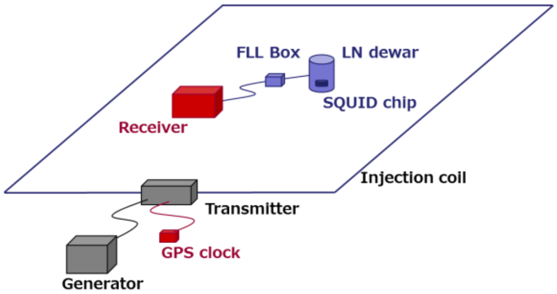

Figure 3: Configuration of the conventional SQUITEM.

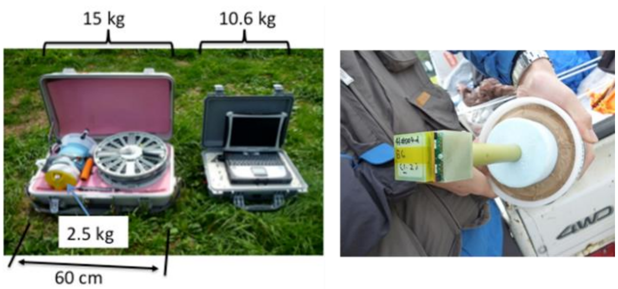

Figure 4: Picture of dewar vessel containing SQUID with receiver unit (left) and SQUID sensor (right).

4.3. Verification Test of the SQUITEM

In order to evaluate whether the SQUITEM can be used for geothermal exploration and its investigation depth, JOGMEC tested the SQUITEM at the Ogiri geothermal field in Kagoshima prefecture of Japan (Fukuda, 2015). Fig. 5 shows the location map of the test field. The transmission loop size was 100 square meters, and its transmission current and its frequency were maximum 25 A and both 0.3 Hz for deep section and 30 Hz for shallow section, respectively. A duty cycle of the transmission wave was 50%. The composite waveform data obtained by the 0.3 Hz and 30 Hz measured data was analyzed using EM1DTM developed by the University of British Columbia.

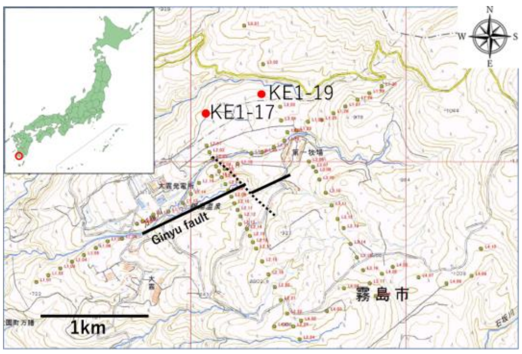

Figure 5: Location map of test field. The yellow circles show the measurement points.

Fig. 6 shows a WSW-ENE cross sectional view of the estimated resistivity structures by the SQUITEM with the results of the electric well logging. The logging results show successively high, low, high resistivity structures from the top layer. According to Gokou (1995), the low resistivity zone corresponds to the smectite and zeolite zones. The analytical results of the resistivity structures by the SQUITEM are consistent well with the logging results excepting the deep zone. As a result, we concluded that the SQUITEM was effective in geothermal exploration, however, its investigation depth is less than 1 km.

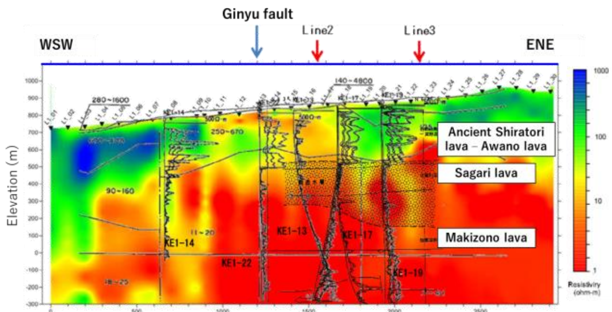

Figure 6: Analyzed resistivity structures by SQUITEM with the logging results. A hatching section in the middle shows the smectite and zeolite zones.

4.4. Improved SQUITEM System

As a result of the mentioned field test, we concluded that the investigation depth of the original SQUITEM system is several hundred meters. However, in geothermal exploration, the desired investigation depth is more than 2 to 3 km. Therefore, in order to increase the investigation depth, we first consider increasing the transmission moment. The signal source of the original system is the grounded loop. However, since the magnitude of the moment depends on current intensity and loop size, further increasing the moment was thought to be difficult considering hardware restrictions and poor measurement efficiency. Therefore, we considered adopting a grounded electric dipole (line source) which is used for the CSAMT. Fig. 7 shows the configuration of our new SQUITEM system. Measurement points are located far from the line source. Once the line source has been installed, measurement requires only the dewar vessel containing SQUID and a liquid nitrogen for cooling the SQUID. Therefore, the measurement efficiency is very excellent even in the mountainous areas.

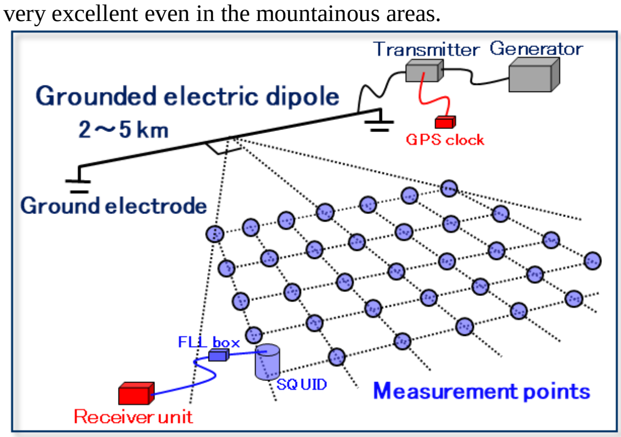

Figure 7: The configuration of new SQUITEM.

Second, we considered extending the measurement time (off-time) of the secondary B-field responses. A current transmission waveform of SQUITEM is a pseudo-sine wave (Fig. 8). Since the investigation depth becomes deeper as the off-time becomes longer, we considered adopting an off-time longer according to the target depth, environmental noises and geological conditions of target fields.

Finally, we are now developing a new transmitter with a strong transmission current of more than 100 A and excellent current interruption performance. We expect this new transmitter can further deepen the investigation depth and improve the signal-to-noise ratio.

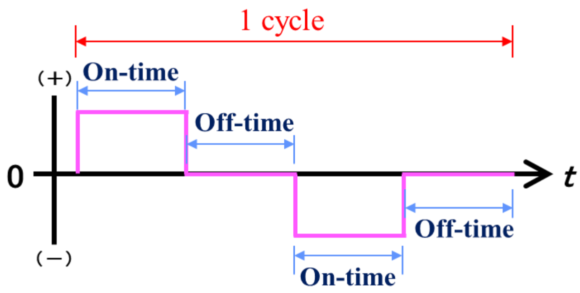

Figure 8: Current transmission waveform of SQUITEM

5. FIELD TEST

5.1 Geological setting

Our test field as shown in Fig. 9 was located on the Yamagawa geothermal field. In the field, Yamagawa geothermal power plant of which the rated output is 30 MW and has been operated by Kyushu Electric power Co., Inc. since 1995. New Energy and Industrial Technology Development Organization (NEDO) who was established as the Japanese governmental organization investigated the field for the purpose of geothermal resource survey in 1999 FY. They reported that quaternary volcanic sediments mainly comprising a tuff are widely and horizontally covered this field. The intrusion of dacite has been confirmed by well surveys. In addition, a powder X-ray diffraction analysis shows that rocks from surface to about 1.6 km depth were altered by hot water and changed to clay rocks mainly comprising montmorillonite.

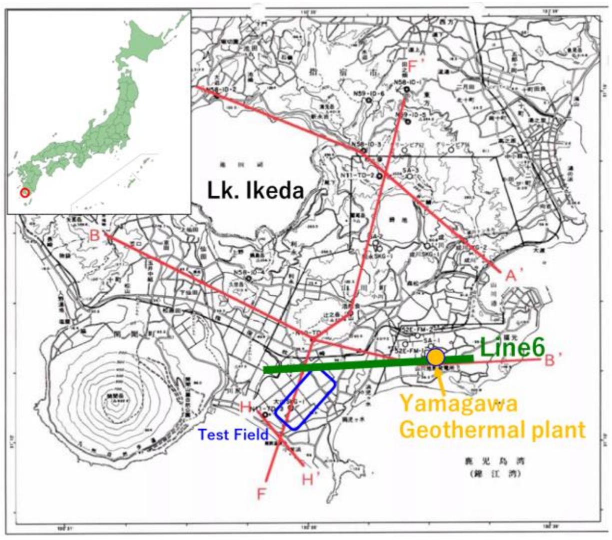

Figure 9: Location map of test field.

5.2 Resistivity structures

NEDO (2001) conducted a 2-D MT survey in this field. Based on the MT survey and various well surveys, they estimated the resistivity structures of this field. Fig. 10 shows an E-W sectional view of the MT result taken along line 6 of Fig. 9 and comprehensive geological interpretation diagram on the line 6. The resistivity structures in this field basically shows a three-layer resistivity structure with successively high, low, high from the top layer. In the report, NEDO concluded that the shallow low resistivity zone corresponded to the montmorillonite zone which played the role of cap-rock. Moreover, they said that the relatively high resistivity zone at the bottom of the low resistivity zone corresponded to the intrusion of dacite. According to the report, the tendencies of the resistivity structures mentioned above can be found in several places in the Yamagawa field. Since there are no wells drilled approximate 3 km depth which is our target depth, we evaluated the investigation depth of our new system based on comparison with the MT results.

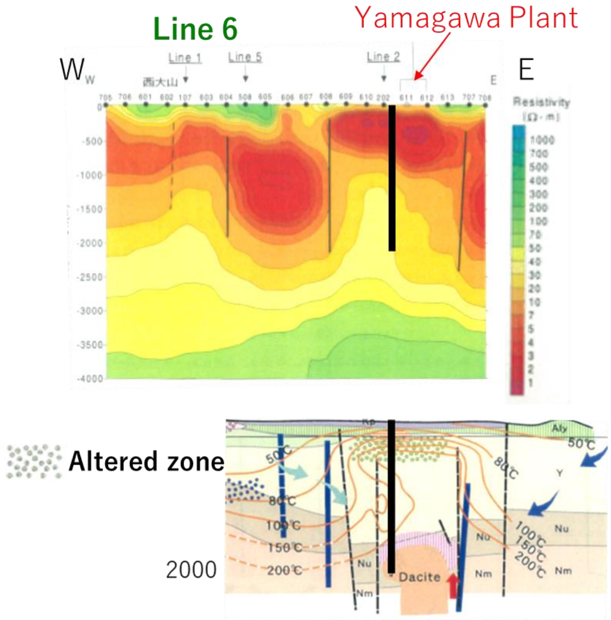

Figure 10: E-W sectional view of the MT result (top) and comprehensive geological interpretation diagram by NEDO (bottom) around Yamagawa geothermal power plant. The green dots show the altered zone and blue arrows show the fluid flow.

5.3 Measurement specification

Fig. 11 shows the measurement configuration of the field test. The brown line and eight red dots on Fig. 11 show the grounded-wire as the signal source and measurement points, respectively. Fig. 12 shows a picture of the dewar vessel which incorporates the SQUID magnetometer. The dewar vessel was buried to avoid the noise due to wind. The signal source length was 2 km and the offset length between the signal source and the measurement points was approximately 1.8 to 3.1 km. Its transmission frequency and its current were 0.025 Hz (10 seconds off-time) and 30 A, respectively. To avoid noises, the measurement points were selected far from noise sources such as high voltage electric wires and radio base stations for mobile phone. Furthermore, in order to reduce incoherent noises, signal data was stacked over 200 times at each measurement points. The average measurement time was about three hours.

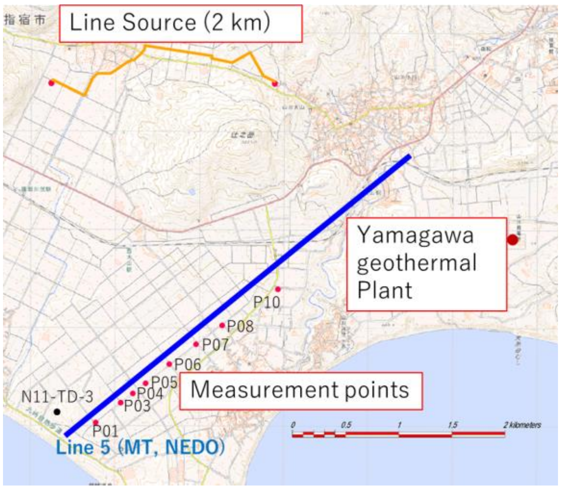

Figure 11: Measurement configuration of field test.

Figure 12: Picture of SQUITEM Dewar.

5.4 Results of the field test

We estimated a 2D resistivity structure by 1-D analysis at the eight measurement points and interpolating the results between the points. Fig. 13 shows a comparison of resistivity structures estimated by the 2-D MT survey and SQUITEM. An overall tendency of the resistivity structures from the SQUITEM is consistent with that of the MT results. The low resistivity zone in shallow section and relatively high resistivity zone at 1.5 km depth in the southeast as shown in the MT result can be also confirmed in the SQUITEM results. Moreover, the resistivity tendency of the SQUITEM in deep section around 3 km is consistent well with the MT result. As a result of the comparison between the MT and this test, we concluded that our new SQUITEM system can offer deep resistivity structures more than at least 2 km with the high measurement efficiency.

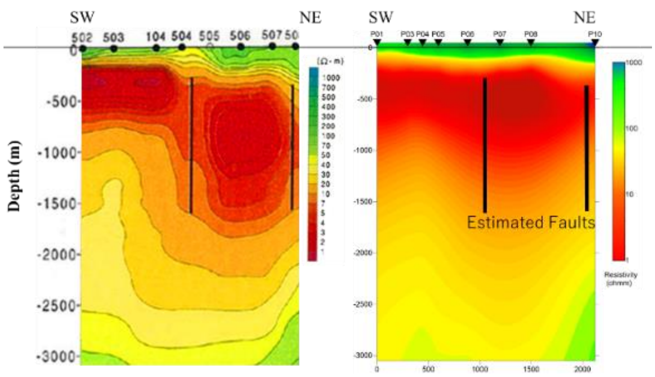

Figure 13: Results of the MT on Line 5 (left) and the SQUITEM (right).

6. SUMMARY

For the high measurement efficiency and high resolution geothermal EM exploration, JOGMEC has developed the SQUITEM system that the signal source is the line source and the off-time can be changed according the target depth. As a result of verification test of the SQUITEM at Yamagawa field, the resistivity structures from shallow to deep section up to 3 km is consistent well with the past MT survey results. Since the measurement efficiency of the SQUITEM survey is better than that of the other EM surveys, and since the investigation depth of the SQUITEM covers from shallow to deep section, we expect that our SQUITEM system becomes one of the standard tools for geothermal explorations like the MT and CSAMT surveys.

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