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Developing a Geothermal TEM System Using SQUID Magnetometer

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ABSTRACT

Since the Fukushima nuclear accident in March 2011, a geothermal power generation is increasingly attracting attention in Japan as it produces less CO_2 than other power generation styles, and it is capable of supplying a baseload electricity for a long term. Although many geothermal development companies or municipality are beginning to investigate for new geothermal resources, relatively high initial survey costs and long lead times are one of the major problems, especially for new geothermal developers. Therefore, JOGMEC which is a Japanese government independent administrative institution has been subsidizing the initial costs and researching and developing technologies aiming to reduce the costs and shorten the survey period. As part of R&D of the technologies, JOGMEC has developed an electromagnetic (EM) exploration system named SQUITEM, which aims to more efficient in term of the measurement including its preparation with equal or higher resolution than the conventional ones. The SQUITEM is a kind of a transient-EM (TEM) exploration system using a SQUID (Super-conducting QUantum Interference Device) magnetometer which has a high resolution compared to the other ones. As the SQUITEM was originally developed by JOGMEC metal/mineral resource exploration team for shallow explorations, we JOGMEC geothermal team improved it suitable for deep geothermal exploration and the survey in the Japanese geothermal fields. We tested our new SQUITEM system at some geothermal fields in Japan to confirm its measurement efficiency and its exploration performance. The results showed that our new system can explore an underground resistivity structure up to more than 2 km depth with the high measurement efficiency.

1. INTRODUCTION

Since the nuclear accident, the Japanese government has been promoting a geothermal development and set a goal to raise a geothermal power generation output up to 520 MW by 2030, which is three times output in 2016. In order to aim the government goal, JOGMEC is technically supporting the geothermal development activity by private company and municipality including financial support. The problems in their geothermal development are the relatively high initial survey costs and the long initial survey period, therefore, JOGMEC is working on three technical themes: exploration, drilling and reservoir management such as an EGS (Enhanced/Engineered Geothermal System) for the purpose of the cost reduction, shortening of the survey period and preventing the decline of the amount of steam. As part of the R&D of the exploration technology, we have been developing an EM survey system that has more efficient in terms of the measurement including its preparation, and equal or higher resolution than that of the other conventional ones. The EM exploration is almost always conducted as one of the initial survey for the purpose of investigating the underground resistivity structure related to a geothermal activity. Although a magnetotellurics (MT) and a controlled source audio-frequency MT (CSAMT) have been conventionally widely used and have many achievements, they have disadvantage in the measurement efficiency in the geothermal field, especially in the Japanese geothermal field. That is because almost geothermal fields in Japan are located in the mountainous area where it is difficult to move around freely since there is a lot of ups and downs, and plants are overgrown. In addition, since there are some valuable plants which are banned to cut down in the survey area, developers have to investigate where they are in advance, and workers have to walk while paying attention not to damage them. Fig. 1 shows the scenery of certain investigation area in Japan. As you can see it, there are lots of tall plants and reforested pines in the center of the picture. When installing the receivers of the MT or the CSAMT, it is necessary to cut down plants as shown in Fig. 2 in order to secure two work paths orthogonal to each other and moreover necessary to dig a hole to bury them, therefore, it takes a lot of time for preparing them. Furthermore, in the case of the MT, its measurement time is more than one night since it has to measure an unstable natural geomagnetic and geoelectric field variation at the Earth's surface. As the measurement efficiency directly affects the costs and survey period, we set out to develop the efficient EM system even in the mountainous geothermal fields.

Figure 1: Example of bush in a Japanese geothermal field.

Figure 2: Bush cutting scenery for securing work paths.

2. EM METHODS IN GEOTHERMAL EXPLORATIONS

2.1 Underground resistivity structure in geothermal fields

A geothermal structure is generally said to be composed of three underground structures: heat, reservoir and geothermal fluids flow. In order to extract a promising geothermal field, it is important to understand these underground structures. Since the EM survey can infer the underground resistivity structure which is strongly related to the reservoir structure and the geothermal fluid flow, it has played a central role in the geothermal investigation. In the geothermal field, the geothermal fluid is stored in a pore space covered by a rock altered by a high temperature geothermal fluid over a long period of time called a cap rock. The cap rock is composed of clay minerals and it usually shows a low resistivity anomaly since the clay minerals can conduct current because of an electric double layered surrounding them. Therefore, the main target of the EM survey is to detect this low resistivity anomaly spreading in relatively shallow zone. Another target of the EM survey is to detect the fracture zones which provide a storage space for the geothermal fluid. Since the fracture zones have a high porosity and store the geothermal fluid, the resistivity seems to show low resistivity, but it is rare to show low resistivity in actual geothermal fields, rather show higher resistivity than that of the cap rock as shown in Fig. 3 which shows a diagram of the thermal and resistivity logs of a geothermal reservoir (Takakura, 2014). Hence it is difficult to directly detect the geothermal reservoir by the EM survey. However, since the reservoir is often formed around faults and intrusive rock which has a high density, namely, high resistivity, it is possible to indirectly know the promising reservoir by detecting a resistivity transition and a local high, resistivity.

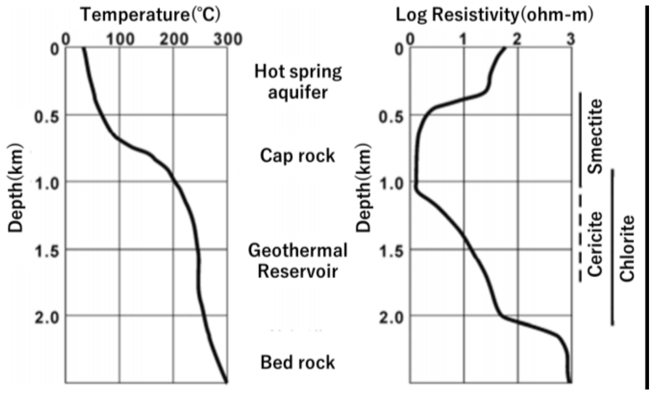


Figure 3: Diagram of the thermal and resistivity logs of a geothermal reservoir modified from Uchida and Murakami (1989) and Takakura (2014). The resistivity of the cap rock is lower than that of the other sections.

2.2 Conventional EM surveys

In geothermal explorations, the MT and CSAMT methods have been widely used since the mid-1900s. Fig. 4 shows a schematic image of the measurement configuration of these methods. 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 structure. The MT has an advantage in the investigation depth, which can be more than hundreds of kilometers by measuring and analyzing a low frequency-band 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 during the measurement. Furthermore, since lots of heavy apparatuses such as coils, batteries and electrodes have to be brought, and it is necessary to make two orthogonal work paths to install four electrodes after a vegetation survey and necessary to dig a hole to bury the receivers for each measurement points, its preparation is quite tough and requires a lot of time and workers in a Japanese geothermal fields. 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 period becomes much shorter than that of the MT. 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. In addition, the preparation difficulty for installing the receivers is same as the MT.

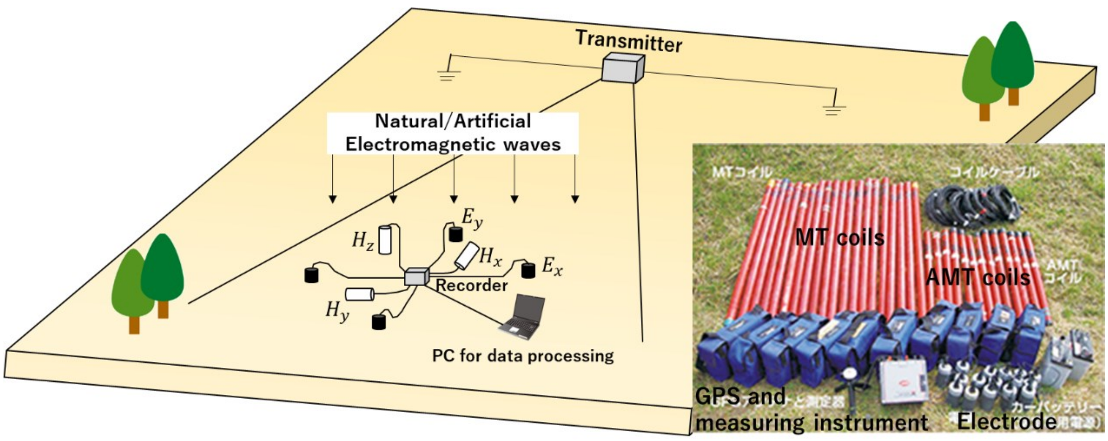


Figure 4: The schematic image of measurement configuration for the MT and CSAMT and a picture of the apparatuses.

3. SQUITEM

Although the MT and CSAMT are useful exploration methods in the geothermal exploration, their measurement efficiency are not good in the mountainous geothermal fields and, moreover in the case of the CSAMT, the investigation depth is too shallow for the geothermal exploration. Hence, the EM method that has the higher measurement efficiency and can investigate from shallow to deep zones is required for the geothermal exploration in Japan. Therefore, we focused on the TEM system using the SQUID magnetometer called SQUITEM which was developed for a shallow metal/mine resource exploration for reasons described below.

3.1 TEM Method

The TEM method is one of 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, a collapsing EM field induces eddy currents in the underground according to Maxwell's equation. These eddy currents produce a secondary B-fields, whose propagation depends on the conductivity distribution in the subsurface as shown in Fig. 5. Unlike the frequency domain EM, the TEM is not affected by a 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 a signal to noise ratio by increasing a transmission moment. Moreover, the measurement time which is between the current off and on can be changed freely according to the target depth.

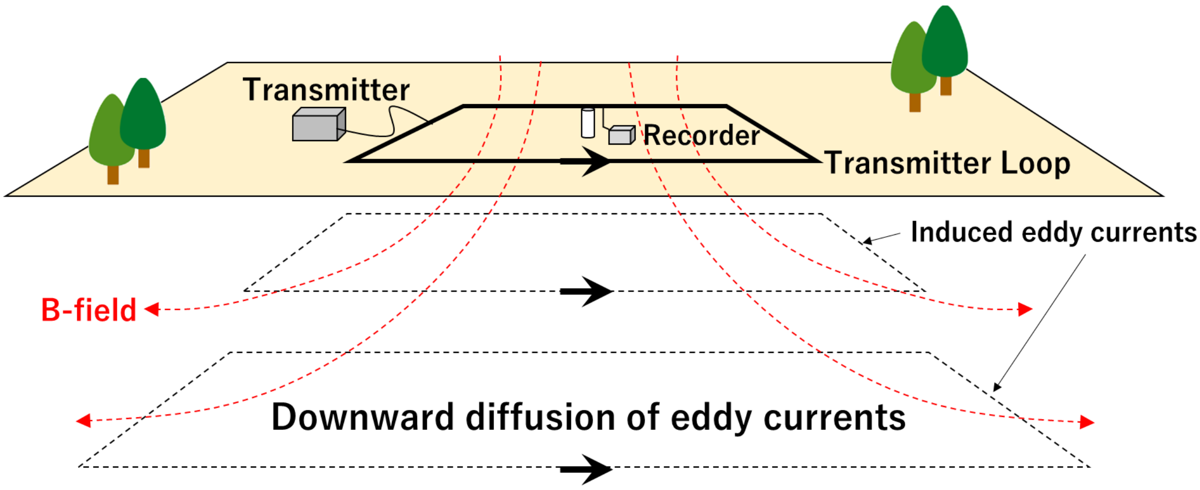
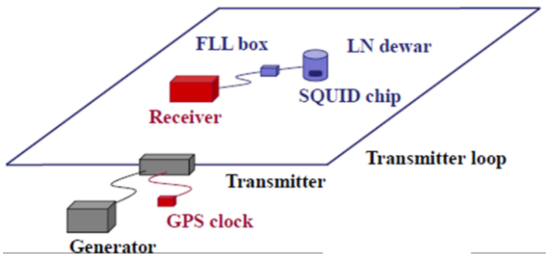


Figure 5: Propagation of eddy currents in underground during the TEM survey.

3.2 Conventional SQUITEM system

Fig. 6 shows a configuration of the conventional SQUITEM system for shallow metal/mine resource exploration. An electric wire connected with a transmitter is installed in a square shape for each measurement points. The SQUID magnetometer is placed in a dewar vessel filled with liquid nitrogen for cooling it. Fig. 7 shows pictures of both the SQUID magnetometer and the dewar. The size of the dewar is 13.5 cm in diameter and 30 cm height, and the weight is 3.5 kg including the liquid nitrogen, which is so small and light that a person can bring easily. The SQUID is connected with a flux locked loop (FLL) which is a used to linearize the SQUID's transfer function, which is connected with a receiver. The receiver can display the observed B-field in real time. The SQUID magnetometer is a high sensitive sensor than the induction coil sensors such as a fluxgate magnetometer which are used in the conventional TEM system. 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 ones. Moreover, the SQUID's bandwidth is from DC to 10 kHz and its dynamic range is 100 dB, which are superior to the other ones. The SQUID can receive even in low frequency signals of the B-field more precisely, therefore, the investigation depth of the SQUITEM is deeper than that of the TEM using the other sensors. Furthermore, 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 SQUITEM is deeper than that of the other TEM.



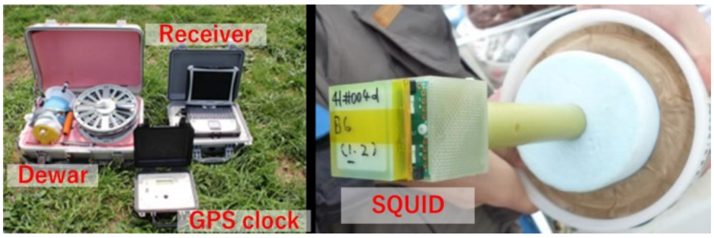


Figure 6: Configuration of the conventional SQUITEM. **Figure 7: Picture of the dewar (left) and the SQUID (right).**

3.3 Verification test of the SQUITEM

In order to evaluate whether the original SQUITEM can be used for the geothermal exploration, we tested the SQUITEM at the Ogiri geothermal field in Kagoshima prefecture of Japan (Fukuda, 2015). Fig. 8 shows a location map of the test field. A reservoir in this field is a fracture zone associated with an activity of the Ginyu fault. The location of the measurement points were decided considering the strike of the fault. 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. Preparation time for each measurement was approximately 30-40 minutes excluding the moving time from the measurement point to the next measurement point. A duty cycle of a transmission wave was 50%, and the investigation time for each measurement point was 5-45 minutes according to the transmission frequency. 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. Fig. 9 shows a resistivity structure on the line 1 provided by the SQUITEM with the logging results. The result shows that the high resistivity structure in shallow zone provided by the SQUITEM is quite consist with the logging results at each wells although the high resistivity structure in deep zone provided by the logging results cannot be seen in the SQUITEM result. As a result, the investigation depth was evaluated as less than 1,000 m depth.

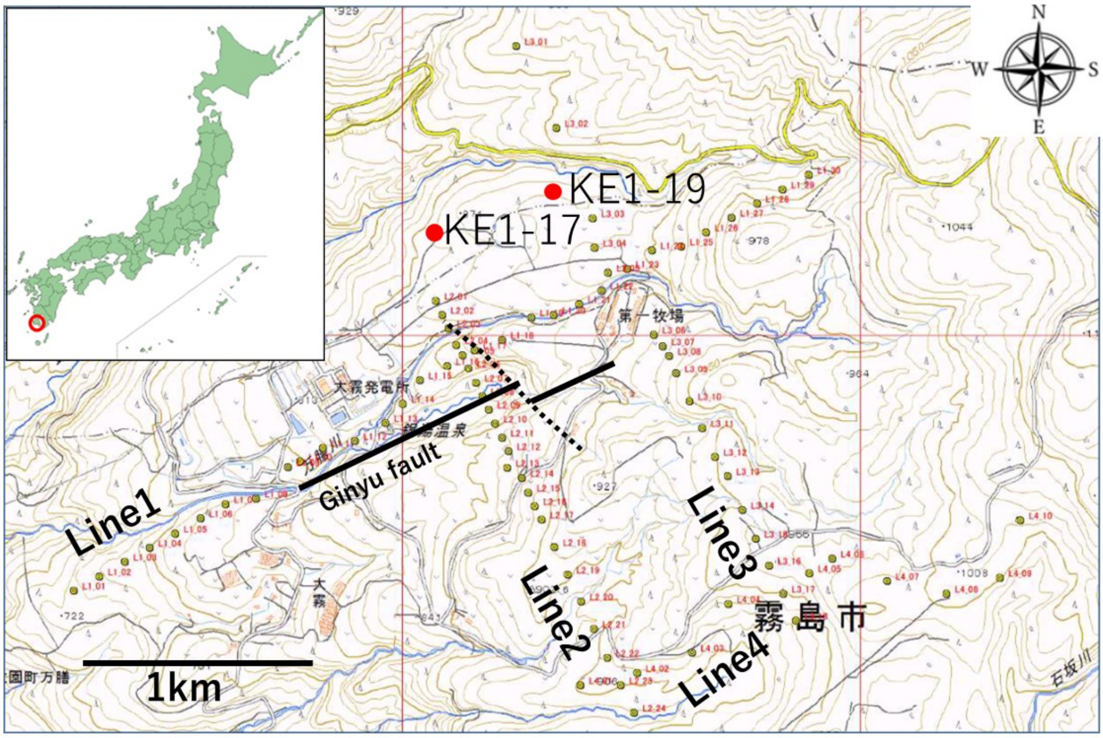


Figure 8: Location map of the test field. The yellow circles show the measurement points.

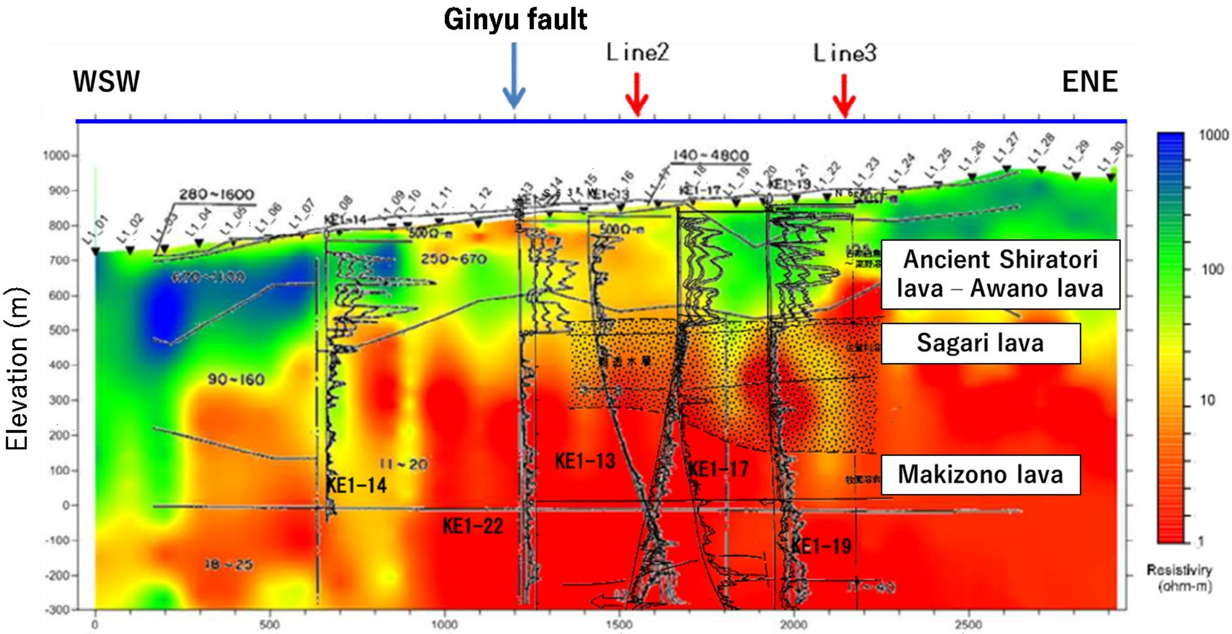


Figure 9: Resistivity structure on line 1 by the SQUITEM with the logging results. A hatching section shows the smectite and zeolite zones.

4.4. Improving the SQUITEM system

As a result of the test in the Ogiri geothermal field, we concluded that although the measurement efficiency was not bad, there was room for improvement, in addition that the investigation depth of the original SQUITEM system was too shallow for the geothermal exploration. Therefore, we set out to improve the original SQUITEM aiming to further increase the measurement efficiency and improve the investigation depth. First of all, in order to increase the investigation depth, we considered increasing the transmission moment. The signal source of the original system is the grounded loop. However, since the magnitude of the moment depends on a current intensity and the loop size, further increasing the moment was thought to be difficult considering hardware restrictions. Therefore, we considered adopting a grounded electric dipole (line source) which was usually used for the CSAMT. By changing from the loop source to the line source, the measurement efficiency has also been improved since the total preparation time for installing the source has decreased. Fig. 10 shows the configuration of our new SQUITEM system. Measurement points are located far from the line source. Once the line source has been installed, the measurement preparation is required only the dewar containing the SQUID.

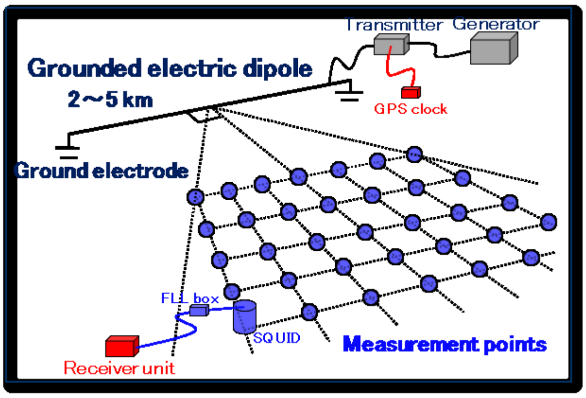


Figure 10: The configuration of new SQUITEM.

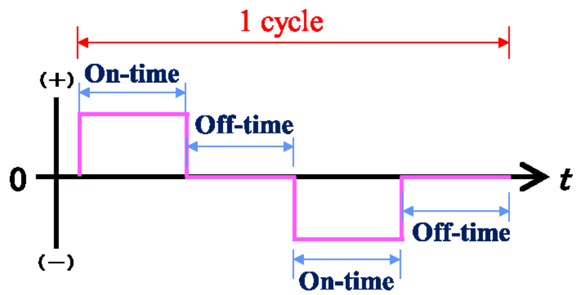


Figure 11: Current transmission waveform of the SQUITEM.

Second, we considered extending the measurement time (off-time) of the secondary B-field responses. A current transmission waveform of the SQUITEM is a pseudo-sine wave as shown in Fig. 11. The original off-time is two seconds. Since the investigation depth becomes deeper as the off-time becomes longer, we considered adopting the off-time longer according to the target depth, environmental noises and geological conditions of target fields. As a result of the below-mentioned test, basically, five seconds off-time is enough for geothermal exploration. Finally, we developed a new transmitter as shown in Fig. 12 with a strong transmission current of more than 100 A and an excellent current interruption performance. In the figure, the metal case on the left is a control and an inverter unit, and the metal case on the right is switching unit. As a result of the laboratory test, a ramp time was 2 microseconds when the transmission current was 100 A. Moreover, we tested it at a mudstone quarry where an environmental noises were small. The length of the line source was 140 m and the fluxgate magnetometer was installed at 90 m far from the line source. Fig. 13 shows the B-field measured by the fluxgate magnetometer when the transmission current was 100 A and the sample rate was 10 kHz. We could confirm that the transmitter could flow more than 100 A of current stably and the current interruption performance was excellent. We expect that this new transmitter can further deepen the investigation depth and improve the signal-to-noise ratio.

Figure 12: Picture of the new transmitter.

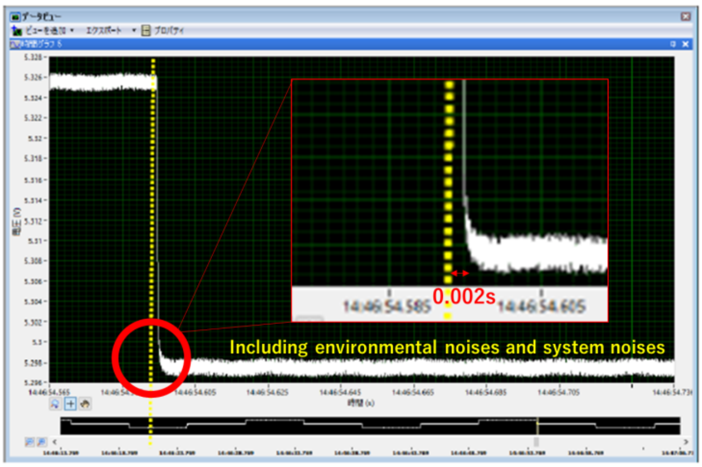


Figure 13: The magnetic field received by fluxgate magnetometer.

5. FIELD TEST

5.1 Location

In order to evaluate the measurement efficiency and the investigation depth of our new SQUITEM system, we tested it in the Yamagawa geothermal field in the southern Kagoshima prefecture of Japan. Fig. 14 shows the location map, and blue rectangular area was our test field on the map. The Yamagawa geothermal power plant which generation output is 30,000 kW is in operation in the east side of the test field, and the Kaimondake volcano is located in the west side of the test field as shown in the Fig. 15. 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. As the 2D MT survey was conducted as part of the geothermal resource survey, we compared SQUITEM's result with the result of the MT survey. At the time of this test, the new transmitter mentioned above was still under development, therefore, we used a commercial transmitter with a 30 A transmission current.

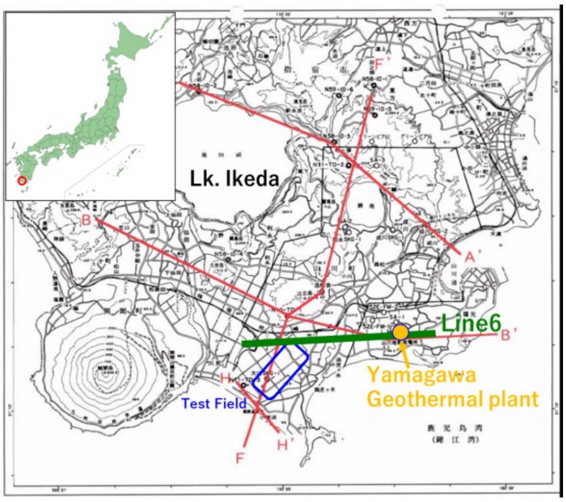


Figure 14: The location map of the test field.

Figure 15: The Kaimondake view from the test field.

5.2 Geological setting

NEDO reported that quaternary volcanic sediments mainly comprising a tuff are widely and horizontally covered this field. The intrusion of a 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. Based on the MT survey and various well surveys, the resistivity structure of this field was estimated. Fig. 16 shows an E-W sectional view of the MT result taken along line 6 on the Fig. 14, and shows a comprehensive geological interpretation diagram on the line 6. The resistivity structure in this field basically shows a three-layer resistivity structure with successively high, low, high from a 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 the dacite. According to the report, the tendency of the local high resistivity structure 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 the comparison with the MT results.

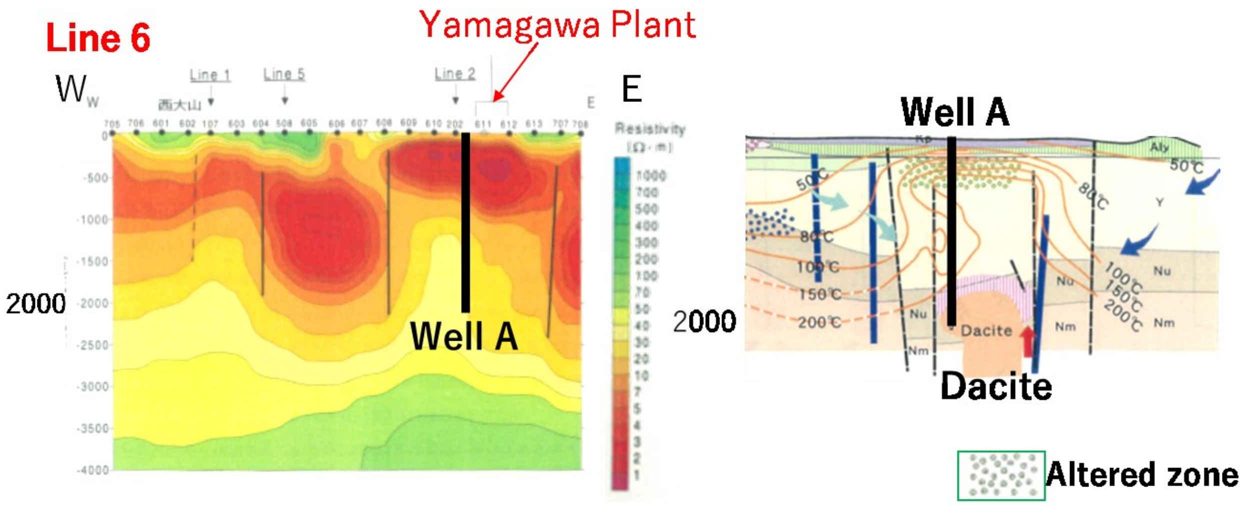


Figure 16: An E-W sectional view of the MT result (left) and a comprehensive geological interpretation diagram by NEDO (right) around Yamagawa geothermal power plant. The green dots in the left figure show the altered zone and blue arrows show the fluid flow.

5.3 Measurement specification

Fig. 17 shows the measurement configuration of this field test. The brown line and eight red dots in the figure show the grounded-wire for the signal line source and measurement points, respectively. It took approximately a week for installing the line source. Fig. 18 shows the dewar which 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 for each measurement points. The average preparation time was less than 20 minutes excluding the moving time and the average measurement time was about three hours per measurement point.

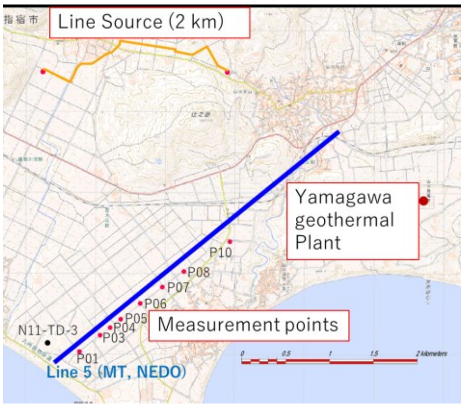


Figure 17: Measurement configuration of field test.

Figure 18: The SQUID dewar buried to avoid window.

5.4 Data analysis

Fig. 19 shows the decline curves at each measurement points of the secondary B-field normalized by the value of the transmission current after stacking a raw data and resampling it. As shown in the figure, the quality of the decline curves are good for analysis. The magnetic flux density was converted to the apparent resistivity as shown in the Fig. 20 for the inversion analysis. The blue line shows an early time data and an orange one shows a late time data at P01 measurement point. The late time reflecting depth information was used for the inversion analysis. We conducted an Occam's inversion using a layered model of which the layer number was 40 and the analysis range was from ground to 3 km. The initial model was created with reference to nearby logging data.

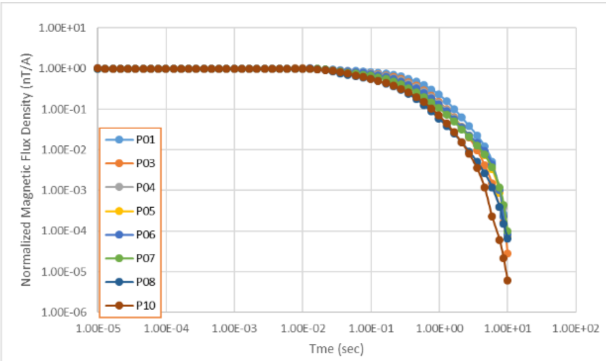


Figure 19: The decline curves at each measurement points.

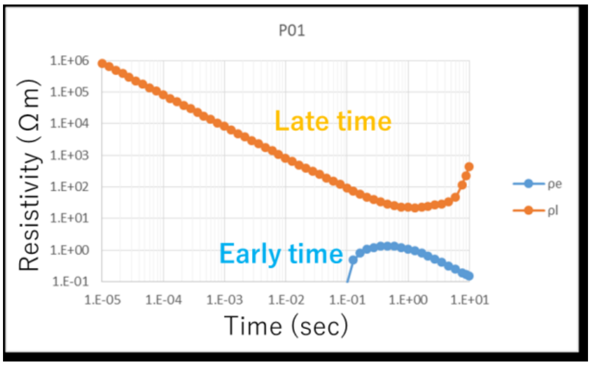


Figure 20: Apparent resistivity curve at P01 point.

5.5 Results of the field test

We estimated a 2D resistivity structure by a 1D inversion analysis at the eight measurement points and interpolating the results using the Kriging method. Fig. 21 shows a comparison of resistivity structures estimated by the 2D MT survey and SQUITEM. An overall tendency of the resistivity structure provided by the SQUITEM is consistent with that of the MT result. The low resistivity zone in shallow zone 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 zone 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.

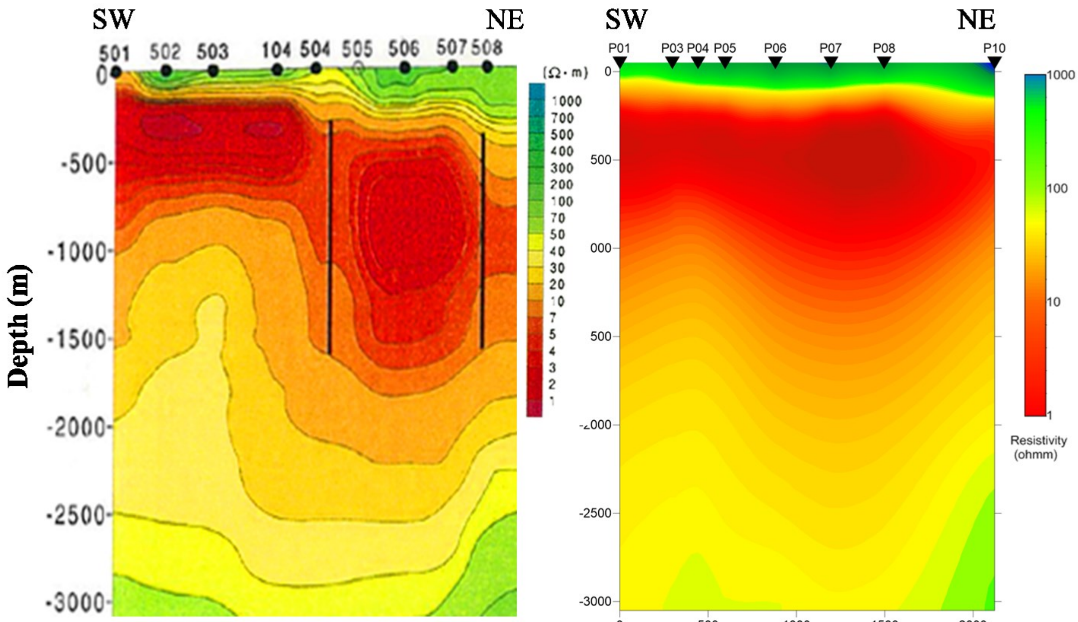


Figure 21: Results of the MT on the Line 5 (left) and the SQUITEM (right).

SUMMARY

Aiming for developing the geothermal EM exploration system which has the high measurement efficiency even in the measurement in the mountainous fields and has the equal or higher resolution than conventional EM explorations, JOGMEC has developed the geothermal SQUITEM system further improved the original SQUITEM for metal/mine resource exploration in terms of the measurement efficiency and investigation depth by adopting the line source instead of the loop source, extending the off-time and developing the new transmitter that can stably conduct large current and has excellent current interrupting capability. As a result of the verification test in the Yamagawa geothermal field, the resistivity structure from shallow to deep zones over 2 km provided by SQUITEM was consistent well with that by the past MT survey. Since our new transmitter which can conduct large current was not used in this test, it was possible that the investigation depth and the resolution may be improved by using it. Moreover, although it is difficult to comparison of the cost between the past MT survey and this test since there is no data regarding the past survey cost, we can say that the measurement efficiency of this test was better than that of the past MT survey: the number of the measurement points per survey period including the preparation time of this test was 1.6 (8 points/13 days), while that of the past MT survey was 0.44 (134 points/59 days). 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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