# DATA ANALYSES OF THE AIRBORNE SURVEY TO CLARIFY THE GEOTHERMAL STRUCTURE AND TO EVALUATE THE GEOTHERMAL POTENTIAL

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## ABSTRACT

Governmental supports at the early stage are necessary for the geothermal energy development in Japan. The national-wide projects for the development were conducted by NEDO, which established in 1980 after the crisis of the oil supply in 1970s'. The "Geothermal Development Promotion Survey" was initiated by NEDO and was aimed to present fundamental geothermal data for the development. In the survey project ground surveys using geological, geophysical, geochemical methods, drilling investigation wells, well logging in the wells were conducted and the geothermal potential in the survey area was estimated by the numerical simulation model.

Following the successful ground surveys, national projects for the early stage development were also requested. A survey using a helicopter was started in 2013 by JOGMEC to find out the fracture system and to evaluate the geothermal resources. There was, however, no precedent for the airborne survey used by a helicopter in Japanese geothermal field, which is usually located in a mountainous region, and therefore operational impracticability was concerned.

This paper will present the outlines of the survey and discuss on the methods to analyze the data.

## 1. INTRODUCTION

### 1.1 Development of the geothermal energy in Japan

No geothermal power plant has been constructed with an install capacity more than 1MW since 1999 in Japan. After the electricity failure and the suspension of the operation in nuclear power plants by the Tsunami disaster in 2011, the geothermal energy came under the spotlight and the demand for the stable energy supply including geothermal energy has been increasing. The Japanese government decided to increase the electricity produced by renewable energy and introduced FIT (Feed In Tariff) for private companies to make the development and the investment easily. As to the geothermal energy development, the government also eliminated the regulation on the development in the national park and made revisions of the JOGMEC law, which integrate the development and the promotion of energies, resulting that JOGMEC (Japan Oil, Gas and Metals National Corporation) has added a new function for the geothermal energy development. The new function includes potential survey, technology developments, and financial supports.

### 1.2 Geothermal Development Promotion Survey

New Energy (and Industrial Technology) Development Organization (NEDO) was settled in 1980 after two energy (oil) crisis in 1974 and 1978. NEDO initiated a survey project named the "Geothermal Development Promotion Survey", which was a strategic nationwide survey and aimed to encourage the development of the geothermal resources by the development enterprises who were nervous because of the risks with resource uncertainties at the initial exploration stage. The survey will contribute to reduce the risk faced by geothermal development companies, to shorten the development term, and to promote the development of geothermal energy.

More than 60 areas were nominated for the survey project. Only five geothermal power plants were constructed out of these survey areas before the suspension of the project in 2010. However the data obtained in the project are of very importance. Almost all attempts for the development of the geothermal energy at present are planed based on the data taken in the "Geothermal Development Promotion Survey".

### 1.3 What is JOGMEC

JOGMEC is a government enterprise with the capital of 502 Billion Yen as of March 2013 and aims to secure stable supply of natural resources, which are oil, natural gas, coal, metals and geothermal energy for Japanese industries and citizens. The action of JOGMEC is based on the Japan Oil, Gas and Metals National Corporation Act, by succession of the functions operated by Japan National Oil Corporation (JNOC), established in 1967, and Metal Mining Agency of Japan (MMIJ), established in 1964, which are both the agencies of Japanese government. Therefore JOMEC has much experience in survey and exploitation of underground resources and takes a roll of the technology development of the geothermal resource.


**Figure 1. JOGMEC was established in February 2004 as one of government companies, succeeding functions of JNOC and MMAJ.**

After the suspension of the electricity supply by the nuclear power plant, the revision of the JOGMEC Act was made, which defines the roll and the target of activity in JOGMEC in September 2012 and JOGMEC took on the additional function of supporting geothermal resource development in Japan as well as that of the coal development overseas. In accordance with the revision of the law and the launch of the new operation, JOGMEC swiftly set up a geothermal resource development support program to cover technological developments, subsidies, equity capital finance and liability guarantees (Nakashima et al., 2015).

### 1.4 Airborne using a helicopter

A new national survey project succeeding "Geothermal Development Promotion Survey" was requested for the development of the geothermal energy. However it was hard to make a project to be supported by national subsidy as there were objections against the NEDO's project. These objections are not based on the scientific point of view but on the political reason. JOGMEC, therefore, planned the survey by a helicopter (hereinafter referred to as heli-borne), where we can obtain geophysical data uniformly over the investigation area and estimate the geological structure for the geothermal resources.

## 2. HELI-BORNE SURVEYS

We conducted heli-borne geophysical surveys aimed to acquire basic data for the evaluation of geothermal resources in order to promote geothermal development.

Most Japanese 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 a useful technique to explore Japanese geothermal fields. JOGMEC conducted gravity survey as well as time domain electromagnetic (TEM) survey using a helicopter to provide an extensive resistivity structure around geothermal fields used as fundamental data for domestic geothermal exploration projects.

Two surveys were conducted in Kuju and Kirishima, where geothermal power plants are operated (Figure 2). The acquired line length is 2,340 km in the Kuju Area and 518 km in the Kirishima Area. These data are processed and

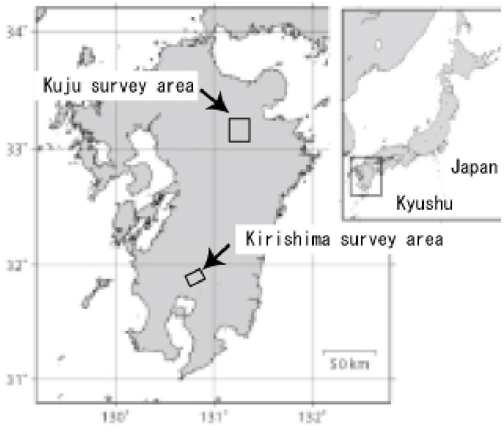


**Figure 2. Areas for the airborne survey in Kyushu.**

interpreted with other geological and geophysical data to evaluate the geothermal potential. The other surveys were carried out in Hachimantai and Yuzawa located in the Tohoku district after the completion of the survey in Kyushu. JOGMEC has a plan to cover most of the geothermal areas by the airborne survey. A lot of heli-borne data will be published and these data are open to the public with a request form to JOGMEC ( http://geothermal.jogmec.go.jp/data/file/data01.pdf/).

### 2.1 Gravity Survey

The heli-borne gravity in our system uses a gravity gradiometer, which measures the spatial variation of the gravitational acceleration, implying that the gravity is measurable with high resolution compared to the conventional gravity survey. The gradiometer measures the gravity tensor (Figure 3) though the conventional gravity meter measures only the vertical component of the gravity vector.

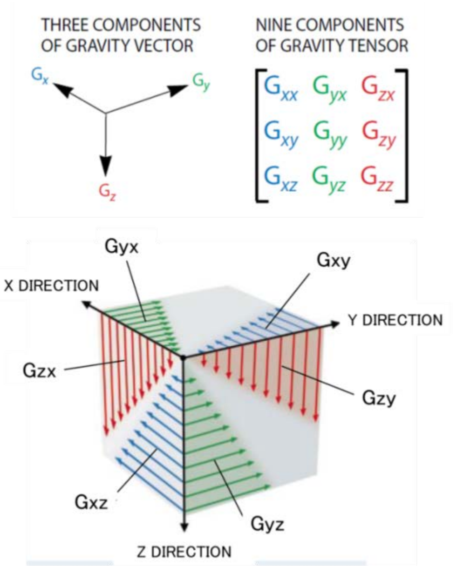


**Figure 3. Gravity potential and tensor (afterBell, 1998).**

As shown in Figure 3, spatial variation of the xyz-axes component of a gravity potential G is represented by the nine tensor components ($G_{xx}$, $G_{xy}$, .. $G_{zz}$). Gravity potential G has several important characteristics. The potential G is one of the solvent of the Laplace equation and potential components are symmetric ($G_{ij} = G_{ji}$). Taking these characteristics into account, there are only five independent components ($G_{xx}$, $G_{xy}$, $G_{xz}$, $G_{yy}$, and $G_{yz}$). If these five are measured, it is possible to uniquely determine the remaining components. The gravity gradiometer survey is capable of measuring these five separate components.

### 2.2 Time-Domain Electromagnetic (TEM) Survey

The TEM survey on the helicopter is 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 $1\times10^6$ $Am^2$. 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. Specification of the TEM system.**

| Transmitter | |
|---|---|
| Loop size | 30m across |
| Base frequency | 25 or 30Hz |
| Time gates | 30 channels |
| Dipole moment | $1.2\times10^6 Am^2$(@+1°C)<br>$1.0\times10^6 Am^2$(@+20°C) |
| Pulse width | 3.7ms |
| | |
| **Reciever** | |
| EM receiver | 3-component X,Y, and Z induction coil sensors |
| Sampling rate | 10Hz |
| Sensitivity | 0.01nT |

### 2.3 Magnetic Field

Total Magnetic Field (TMF) is obtained by the magnetometer using nuclear magnetic resonance attached to the TEM system. The sampling rate for the magnetic data is 10 Hz. The magnetometer covers the range of 15,000nT and 100,000nT with an accuracy of 0.001nT.

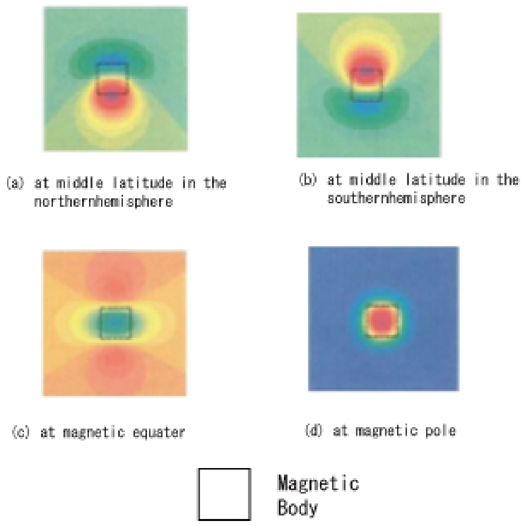


**Figure 4. Examples of the magnetic anomalies. Anonalies are NOT observed over source bodies at the region in the middle latitude (after SEGJ, 1989).**

Magnetic field varies with time due to the diurnal change and the magnetic storm. In order to compare the spatial change the estimation of the diurnal change is important. The data for the estimation of the diurnal change are sampled at 1Hz. The data are imported into a database and filtered with a 50 second Hanning filter (window) to smooth spikes and short wavelength variations. The local regional field value of 47400 nT for Kujyu and 47100 nT for Kirishima, calculated from the average of the data, was removed from the original data.

The correction of date, altitude of the sensor and offset by the IGRF (International Geomagnetic Reference Field) average, 47310 nT for Kujyu and 46740 for Kirishima, was also applied to obtain the final Total Magnetic Intensity (TMI). The IGRF was calculated using the 2010 IGRF model for the specific survey location.

In the middle latitude like Japan, magnetic field anomalies have an offset from the centre of the magnetic body due to the horizontal component of the induced magnetization (Figure 4). Magnetic anomaly appears above the magnetic body when the measurement is carried out at the pole. Therefore, RTP (Reduce to the Pole) filter is often used to locate magnetic anomalies over source bodies.

## 3. DISCUSSION

### 3.1 Gravity

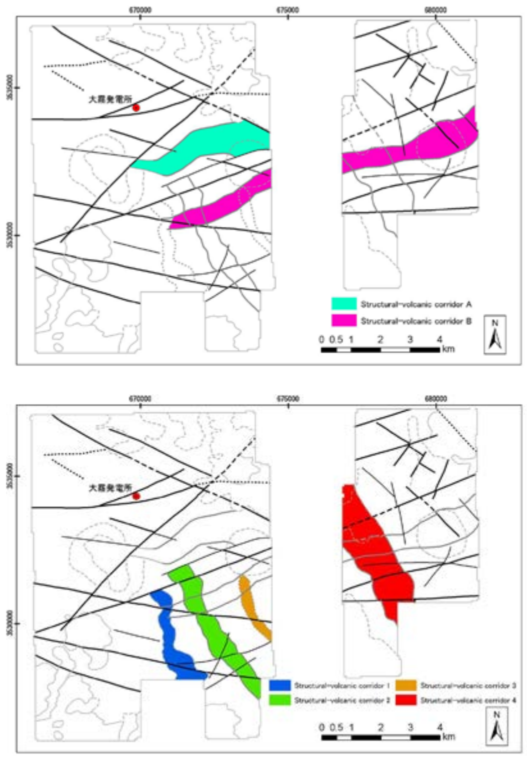

**Figure 5. Interpretation maps in Kirishima Area with low gravity responses. (a) ENE-WSW structure indicating major geothermal reservoirs (b) NNW-SSE composed of conjugate faults.**

The Kuju area, one of the survey areas in Kyushu, is located in the Beppu-Shimabara Graben, where normal faults and extensional tectonic stress are often observed (e.g. Kamata, 1989). The graben was caused by the upflow of the mantle (Continental Rift) or right lateral fault movements (Pull-apart Basin). The most prominent and continuous fault structures mapped from the gravity gradiometer data in the area are NW-SE trending. Another important set of faults, mostly located in the south of the survey area, is roughly ENE-WSW trending. This set seems to be slightly sigmoidal in map view, changing from more EW orientation in the west to ENE-WSW in the east (Shimada et al., 2015).

In Kirishima area low gravity responses with ENE-WSW and NNW-SSE trendings are often found in the map taken by the gradiometer, which are interpreted as normal-sinistral, transtentional faults (Figure 5). These predominant normal components are interpreted from literature (Goko, 2000). The major geothermal resources are found along the faults with an ENE-WSW trending and the NNW-SSE structures are interpreted as a conjugate structure with adjustment of hot water flows.

### 3.2 TEM

#### 3.2.1 Calibration

For each flight two sets of the calibration, the pre-flight calibration and the post-flight calibration, are made, which consists of measuring the system characteristics out of ground effect and compensation of the electromagnetic data. The calibration has to be made at the high altitude enough to avoid the subsurface effect on the data. The flight height was set to be 2,500ft high. During the pre- and post-flight calibration a minimum of 30 seconds of data is collected to monitor the effectiveness of the calibration and the accuracy to the base levels. Both data are compared to quantify the drift of the equipments. Figure 6 shows typical flight schedule for the TEM measurement.

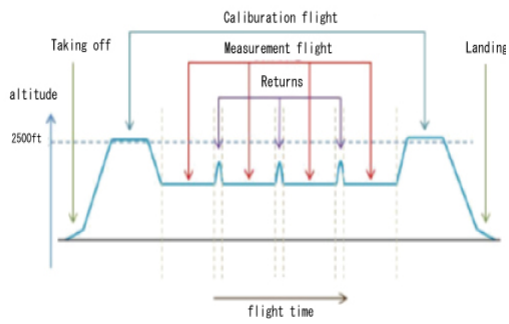


**Figure 6. An example of the flight schedule. Two sets of the calibration flight are scheduled for evaluation of the ground effects, magnetization of the helicopter body.**

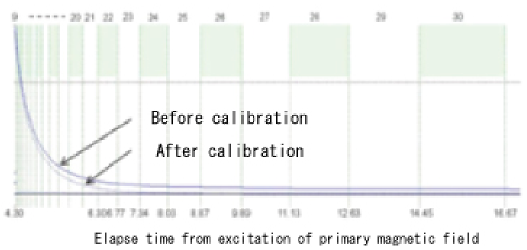


**Figure 7.The intensity decline of the primary magnetic field and the removal of the magnetic effects of the helicopter body.**

#### 3.2.2 Time Window

The amplitude of the signals detected in three induction coils decreases rapidly with time. Time windows are set for the signal sequence and the mean value in the window is calculated for the data in the analysis. We have selected 30 windows from 0.065ms to 16.667ms (Figure 7 and Table 2). The signals detected in the induction coils represent the secondary magnetic field excited in the subsurface. The deeper magnetic field appears in the later signals. Therefore the signals in the later window gate contain the resistibility information at the deeper part.

**Table 2. Gate position**

| Gate | Start (ms) | End (ms) | Midpoint (ms) | Width (ms) | |
|---|---|---|---|---|---|
| 1 | 0.065 | 0.146 | 0.106 | 0.081 | Ontime |
| 2 | 0.977 | 1.961 | 1.469 | 0.985 | Ontime |
| 3 | 1.953 | 2.450 | 2.201 | 0.496 | Ontime |
| 4 | 3.882 | 3.971 | 3.927 | 0.090 | Ontime |
| 5 | 4.183 | 4.199 | 4.191 | 0.016 | Offtime |
| 6 | 4.199 | 4.224 | 4.211 | 0.024 | Offtime |
| 7 | 4.224 | 4.256 | 4.240 | 0.033 | Offtime |
| 8 | 4.256 | 4.297 | 4.277 | 0.041 | Offtime |
| 9 | 4.297 | 4.346 | 4.321 | 0.049 | Offtime |
| 10 | 4.346 | 4.403 | 4.374 | 0.057 | Offtime |
| 11 | 4.403 | 4.468 | 4.435 | 0.065 | Offtime |
| 12 | 4.468 | 4.541 | 4.504 | 0.073 | Offtime |
| 13 | 4.541 | 4.622 | 4.582 | 0.081 | Offtime |
| 14 | 4.622 | 4.712 | 4.667 | 0.090 | Offtime |
| 15 | 4.712 | 4.810 | 4.761 | 0.098 | Offtime |
| 16 | 4.810 | 4.932 | 4.871 | 0.122 | Offtime |
| 17 | 4.932 | 5.111 | 5.021 | 0.179 | Offtime |
| 18 | 5.111 | 5.330 | 5.221 | 0.220 | Offtime |
| 19 | 5.330 | 5.591 | 5.461 | 0.260 | Offtime |
| 20 | 5.591 | 5.908 | 5.750 | 0.317 | Offtime |
| 21 | 5.908 | 6.299 | 6.104 | 0.391 | Offtime |
| 22 | 6.299 | 6.771 | 6.535 | 0.472 | Offtime |
| 23 | 6.771 | 7.340 | 7.056 | 0.570 | Offtime |
| 24 | 7.340 | 8.032 | 7.686 | 0.692 | Offtime |
| 25 | 8.032 | 8.870 | 8.451 | 0.838 | Offtime |
| 26 | 8.870 | 9.888 | 9.379 | 1.017 | Offtime |
| 27 | 9.888 | 11.125 | 10.506 | 1.237 | Offtime |
| 28 | 11.125 | 12.630 | 11.877 | 1.506 | Offtime |
| 29 | 12.630 | 14.453 | 13.542 | 1.823 | Offtime |
| 30 | 14.453 | 16.667 | 15.560 | 2.214 | Offtime |

#### 3.2.3 Data Processing

The following processing steps are applied to the signals;

1) Apply the calibration to remove spike noise, coil oscillation
2) Noise filtering and stacking the data
3) Filtering to remove the effect of the residual and nonlinear drift
4) Levelling to compensate of the amplitude difference for each survey line used the averaged amplitude in the latest window

Figure 8 shows the analysis result of the TEM measurement for a survey line. Each result line represents the output of the induction coils in the window. Figure 9 shows the

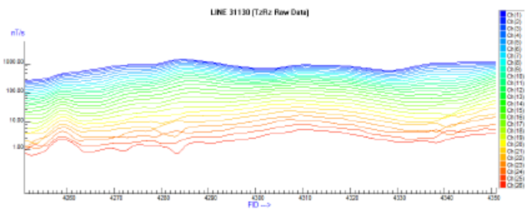

**Figure 8.An example of the TEM measurement. Each line indicates the change of the window value.**

resistibility profile calculated from the data shown in Figure 8.

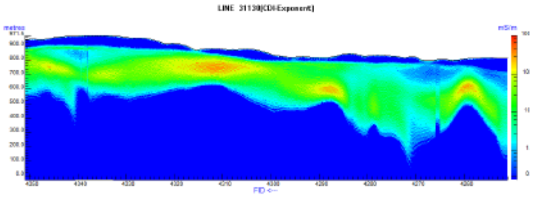

**Figure 9. Calculated resistibility profile.**

### 3.2.4 Comparison to surface survey

In order to verify the airborne data quality in Kirishima areas, we carried out the measurement by the SQUITEM, a ground-based TEM system 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. The SQUITEM survey was conducted to obtain the validation of the TEM measurement by a helicopter. 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

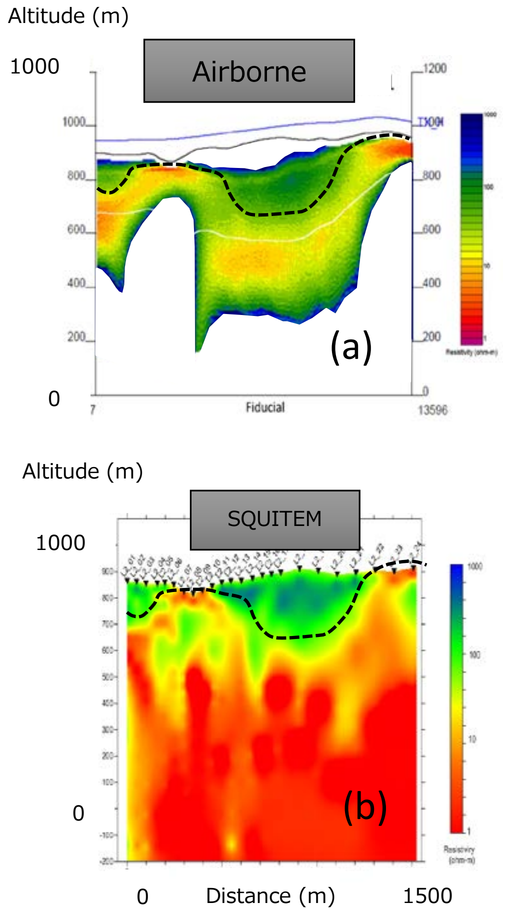


**Figure 10. (a)A profile take by the airborne survey, (b) A profile taken by SQUITEM**

CSAMT and AMT. The consistency of the results analyzed by those two measurements, SQUITEM and CSAMT/AMT on the surface, was obtained (Fukuda et al., 2015).

The comparison between the result taken by the SQUITEM system and that in TEM in a helicopter was conducted and discussed by Fukuda and Tosha (2015), resulting that resistibility profiles by two measurements were quite similar (Figure 10).

### 3.3 Magnetic Field

A rock generates the gravity and the magnetic field. The gravity (dφ) and magnetic (dΨ) potentials at the observation point (P) far away from the rock with a distance of r and a volume of dv are

$$d\varphi = G\rho\left(\frac{1}{r}\right)dv,$$

$$d\Psi = k\mathbf{J}\frac{\partial}{\partial \boldsymbol{i}}\left(\frac{1}{r}\right)dv$$

where G and k are the gravitational and the magnetic field constants, respectively.

$\rho$ and J are density and magnetization of the rock. $\boldsymbol{i}$ is the direction of the magnetization.

We can get the relationship between gravity and magnetic potentials (Poisson's equation),

$$d\Psi = \frac{k}{G}\frac{\mathbf{J}}{\rho}\frac{\partial}{\partial \boldsymbol{i}}(d\varphi)$$

We also get the other equation by differentiation of Z

$$\frac{\partial\Psi}{\partial z} = \frac{k}{G}\frac{\mathbf{J}}{\rho}\frac{\partial}{\partial \boldsymbol{i}}(g_z)$$

This equation means that the ratio of the z-component of the magnetic potential to the component of the magnetization direction of gravity is constant. This relation is satisfied if the ration of the magnetization to the density is constant. Although the density and the magnetization of the subsurface rocks are various, the uniformity can be assumed in a narrow area. In the moving-window Poisson's method proposed by Chandler et al.(1981), we will divide several small regions of the survey area and apply the Poisson's equation to each region. Kaziwara and Mogi (2008) applied this method to the structure analysis in Japan and showed the location of the faults. This technique will be applied to the airborne survey data.

## 4. CONCLUSIVE REMARKS

The airborne survey using a helicopter has been in operation. Gravity gradient, TEM and magnetic field were measured. Several analysis techniques were applied to each measurement and consistent results to the geological settings were obtained. At the next step we have to integrate the analyzed results to estimate the geothermal resources at the investigated area.


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