Airborne Gravity, Electromagnetic and Magnetic Data for Geothermal Exploration

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ABSTRACT

Advances in airborne geophysical technologies have enabled rapid and efficient acquisition of high-resolution gravity, electromagnetic and magnetic datasets in rugged volcanic terrains.

HeliFalcon® airborne gravity gradiometer (AGG), and Helitem® airborne electromagnetic (AEM) and magnetic systems have been used to acquire high-quality multiphysics datasets which have proven effective for geothermal exploration.

A case study from a project in Japan is used to demonstrate how the acquisition, processing, and integrated interpretation of high-resolution airborne datasets, along with other available information, is providing significant benefit to geothermal assessment programs.

1. INTRODUCTION

In 2013, JOGMEC (Japan Oil, Gas and Metals National Corporation) began a series of airborne geophysical programs over areas of known and potential interest for geothermal exploration throughout Japan.

It was recognized that geological information was not sufficient for geothermal exploration and assessment in many areas, and its development was not progressing. The airborne geophysical survey was conducted for the purpose of promoting geothermal resource development.

The surveys required airborne systems capable of operating in, and acquiring high-quality and high-resolution data over, the mountainous terrain found in most of the survey areas.

HeliFalcon® airborne gravity gradiometer (AGG), and Helitem® airborne electromagnetic (AEM) and magnetic systems were selected to undertake the surveys. These surveys have continued to be undertaken each year since 2013. The acquired high-quality multiphysics datasets, and accompanying integrated interpretations, have been made available to geothermal companies to de-risk and promote geothermal development.

2. HELIFALCON AIRBORNE GRAVITY GRADIOMETRY

Falcon AGG and HeliFalcon AGG are airborne gravity gradiometer technologies which acquire high resolution gravity data.

The Falcon AGG technology was originally developed in a collaborative project between BHP Billiton and Lockheed Martin which adapted US Navy technology into practical instrumentation for deployment in light fixed wing and helicopter aircraft. Xcalibur Multiphysics have owned and commercially operated the Falcon and HeliFalcon AGG technologies since 2008.

Lee (2001) described the Falcon AGG technology, while Lee et al (2006) described the introduction of the HeliFalcon AGG technology. Christensen et al (2015) presented a detailed analysis of noise and repeatability of Falcon AGG data, and a comparison with high resolution ground gravity data.

HeliFalcon is the only AGG system operable on a helicopter, and capable of flying in mountainous terrain. The system deployed in Japan shown in Fig.1. In addition to gravity data, the system acquires DGPS navigational and positional data, and high-resolution laser scanner DTM data which is used to calculate rigorous terrain corrections for the gravity data. The system can also be configured to simultaneously acquire stinger magnetics if required.



Figure 1: A HeliFalcon system acquiring high-resolution gravity data in Hokkaido, Japan.

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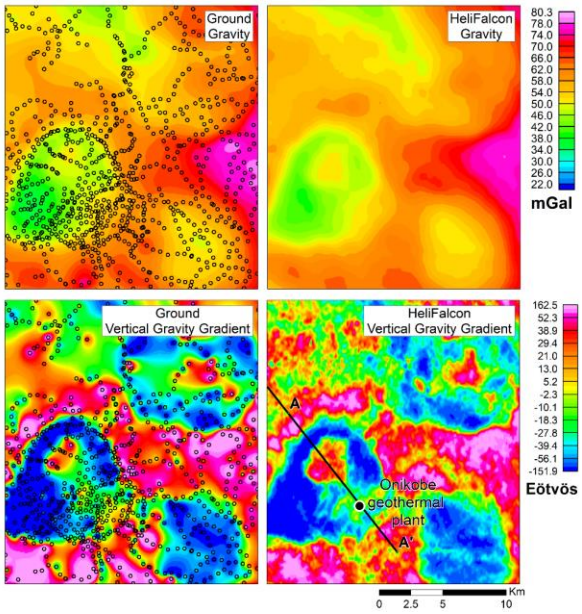


Figure 2: Comparison of HeliFalcon and ground gravity data around Onikobe Caldera, Honshu, Japan.

An HeliFalcon validation survey was flown over an area of existing ground gravity data around the Onikobe Caldera. Comparative gravity and vertical gravity gradient data is shown in Fig.2. The ground data images show the ground gravity station locations, while the HeliFalcon was flown at 250 line spacing, with some areas of 125m infill.

The ground gravity was challenged by lack of ground access for gravity readings due to mountainous terrain, volcanos, lake, and cultural restriction, resulting in degradation of the resolution of the ground gravity dataset. By comparison the HeliFalcon data had unrestricted access to the survey area, allowing gravity readings at regular intervals, and at higher density, resulting in significantly high data resolution.

In the survey area shown, the Onikobe (W), Hanayama (SE) and Kurikomayama (NE) caldera structures are mapped. The area also contains fumaroles and numerous hot springs.

The Onikobe geothermal power plant is located on the edge of high gravity gradient anomalies inside of the low gravity gradient zone. Figure 3 shows a profile of the gravity gradient along the line A-A' in Figure 2 with the geological section. The variation of the gravity gradient is agreeable to the upper boundary of the granitoid basement rock and images features of geothermal significance around the plant.

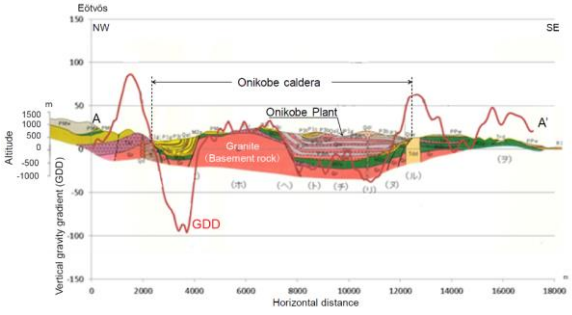


Figure 3: Profile of HeliFalcon gravity gradient data along line A-A' through the Onikobe Geothermal Plant shown in Fig. 2. From Chiba (2016)

HeliFalcon AGG data is used in geothermal exploration to accurately map the spatial distribution of lithologies, and tectonic and volcanic structures.

3. HELITEM^2 AIRBORNE ELECTROMAGNETICS

Helitem^2 is a helicopter time domain electromagnetic system which acquires high resolution ground conductivity data. Smiarowski (2020) described the Helitem^2 system.

Helitem^2 is designed for maximum depth of exploration and sensitivity to target. To meet the maximum depth design goal, it features:

- coincident geometry
- a large diameter transmitter loop, 35m standard or 21m loop for improved terrain/altitude performance,
- high-power square waveform transmitter
- ultra-low transmitter frequencies down to 6.25Hz
- large diameter, low-noise receiver

The Helitem^2 AEM system is shown in Fig. 4. Magnetic data is simultaneously acquired with the electromagnetic data.

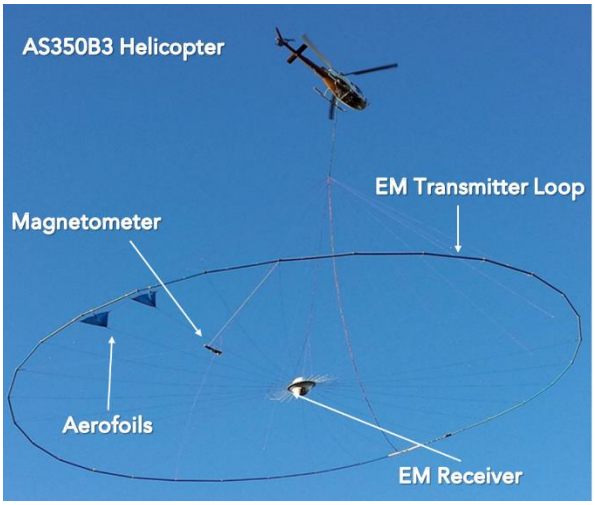


Figure 4: A Helitem^2 AEM system acquiring high-resolution electromagnetic and magnetic data.

Helitem data from a survey in Japan (acquired with an earlier Helitem system) is shown in Fig.5.

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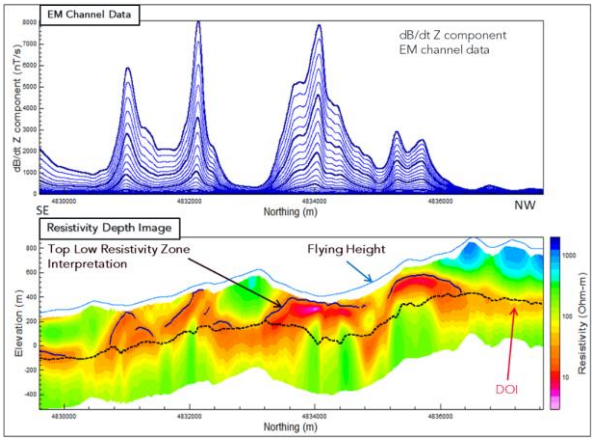


Figure 5: Helitem Channel data and RDI from Japan

The top panel of Fig. 5 shows a survey line of dB/dt channel data, while the bottom panel shows the same line processed into a Resistivity Depth Image (RDI) using the UBC 1DTM inversion algorithm.

Also shown on the Resistivity Depth Image are the Helitem system flying height, the estimated reliable depth of investigation (DOI) (which ranged from approximately 300m to 500m over the full extent of the survey), and the interpreted Top of the Low Resistivity Zone (Geothermal Clay-Cap).

Helitem AEM data is used in geothermal exploration to accurately map low resistivity zones which may indicate hydrothermal alteration, the distribution of primary lithologies, and tectonic and volcanic structures.

Magnetic data acquired simultaneously with the electromagnetic on Helitem AEM surveys is used to map reduced susceptibility zones which may indicate magnetite destruction caused by hydrothermal alteration, as well as spatial distribution of lithologies, and tectonic and volcanic structures.

4. MUSADAKE-TESHIKAGA CASE STUDY, HOKKAIDO, JAPAN

During 2015-16, JOGMEC acquired 9,932 line-km of HeliFalcon® AGG data and 5,567 line-km of Helitem® AEM and magnetic data over the Musadake-Teshikaga area in NE Hokkaido. See Fig. 6.

The data were acquired and interpreted in conjunction with other existing data with the aim of assisting the identification of prospective areas for geothermal in the Musadake-Teshikaga area, Hokkaido, Japan.

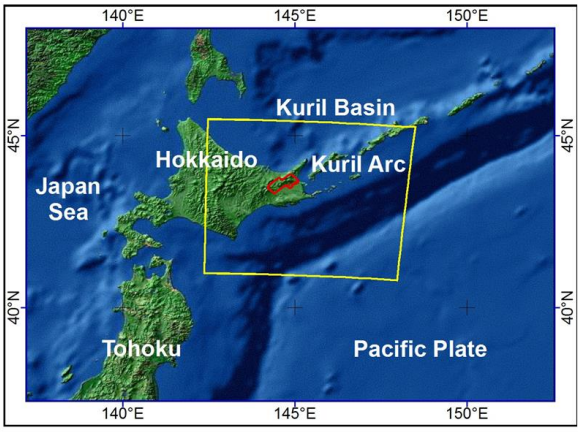


Figure 6: Musadake-Teshikaga Area Location

4.1 Acquired Airborne Geophysical Datasets

Falcon AGG data, magnetic data, and Helitem AEM data were acquired. This data can be enhanced and displayed in various ways. Examples of these three datasets are shown respectively in Fig. 7, Fig. 8 and Fig. 9.

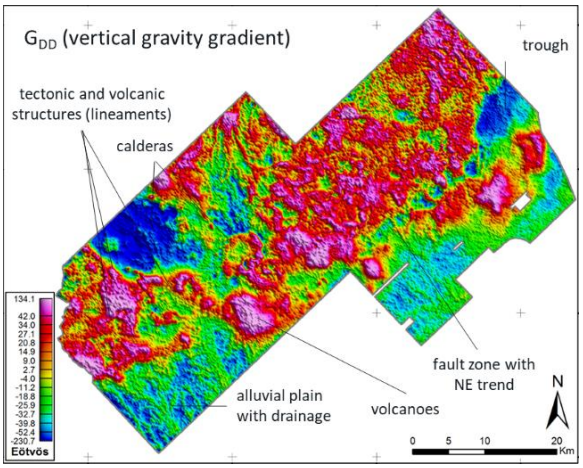


Figure 7: Falcon AGG Data – Vertical Gravity Gradient (G_{DD})

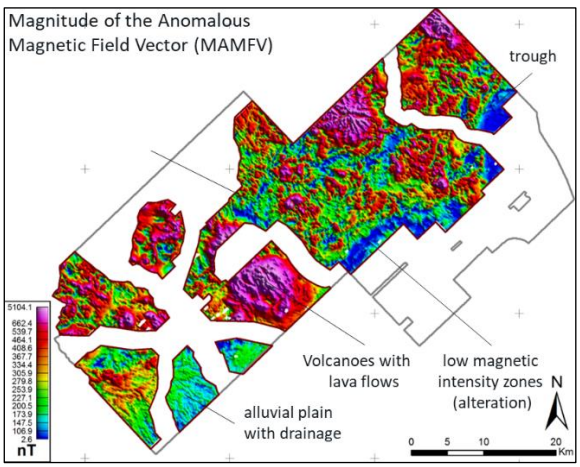


Figure 8: Magnetic Data – Magnitude of the Anomalous Magnetic Field Vector (MAMFV)

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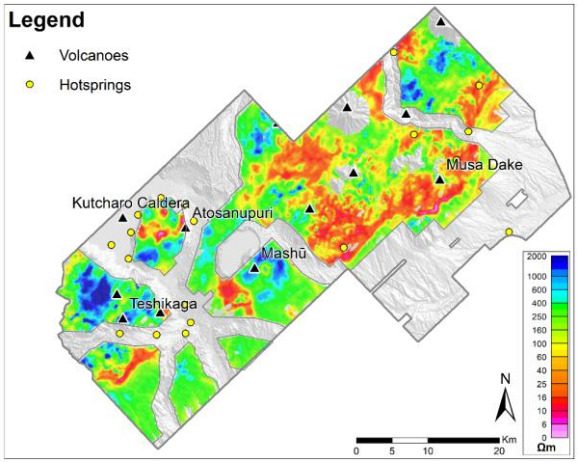


Figure 9: Helitem AEM Data – Resistivity Depth Slice at 100m above mean sea level

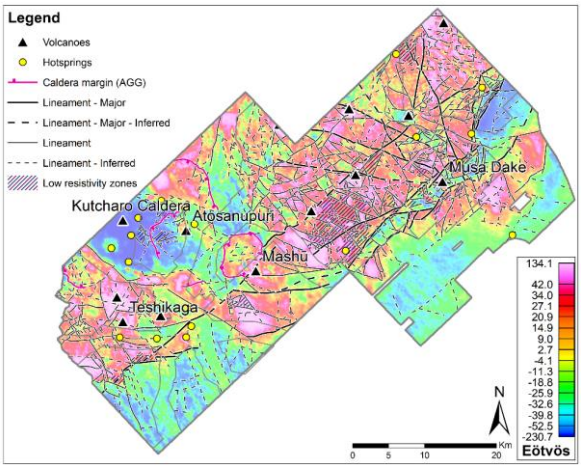


Figure 10: Integrated Interpretation on AGG Vertical Gravity Gradient Data (G_{DD})

4.2 Integrated Interpretation

The integrated interpretation focused on delineating key tectonic and volcanic structures in the airborne geophysical datasets to assist in identifying prospective areas for further geothermal exploration.

Initially the regional geological setting was investigated using public domain data. Then interpretation of individual datasets, Gravity Gradient, Magnetic and EM were undertaken separately.

Lithologies and structures were mapped in ArcGIS. Both lineaments and concentric boundaries were mapped, with the latter interpreted to be caldera ring faults.

Low resistivity zones were interpreted using the AEM data, both in map form and on resistivity depth sections. These low resistivity zones, which may indicate the presence of clays associated with hydrothermal alteration, are commonly associated with discrete magnetic lows in the magnetic maps. The reduced magnetic susceptibilities may reflect thermal destruction of magnetite and/or chemical alteration processes such as the conversion of magnetite to pyrite.

Finally, all the individual interpretations were integrated into one map, and prospective zones for further geothermal exploration were derived from the integrated interpretation of the combined airborne datasets.

Figures 10, 11 and 12 show the integrated interpretation displayed on backgrounds of gravity, magnetic and electromagnetic data respectively.

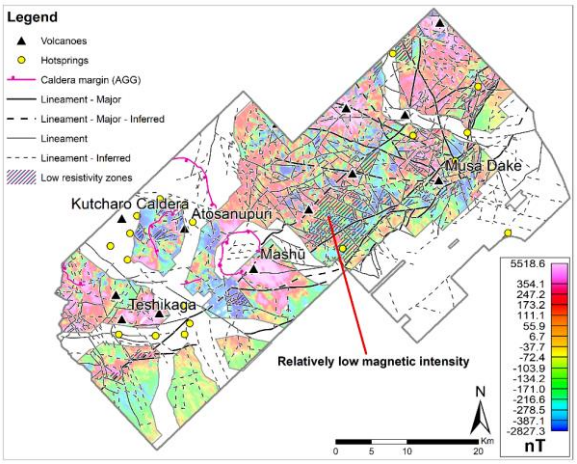


Figure 11: Integrated Interpretation on Magnetic Data (differential RTP of the Residual Magnetic Intensity)

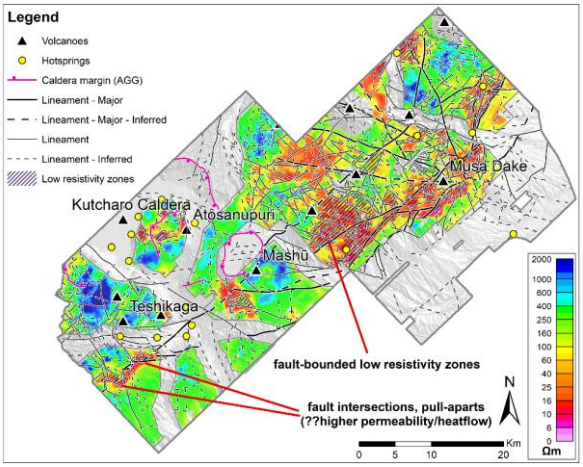


Figure 12: Integrated Interpretation on a Resistivity Depth Slice at 100m above mean sea level

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4.3 Further Analysis of the Helitem AEM Data

To gain a better understanding of the 3D lateral and vertical resistivity distribution in the survey area, inversions were run on the Helitem data using UBC's 1DTM inversion code.

Resistivity Depth Images were generated for all survey lines, as shown previously in Fig.5.

A 3D resistivity voxel (short for volume pixel) model, shown in Fig.13, was calculated from the RDI profiles, by interpolating between the profiles using a minimum curvature 3D gridding algorithm. The cell sizes of the Musadake and Teshikaga area voxel model are 125 m by 125 m laterally (in the Easting-Northing plane) and 14.5 m vertically (in depth).

The 3D Voxel model was then used to extract resistivity depth slices (See Fig.12), and data subsets including the resistivity Iso-surface shown in Fig 14., which extracts the lower resistivity (<25 Ωm) volumes within the model to visualize the 3D distribution of the more conductive rocks, interpreted as the low resistivity zones. These zones include abundant clay caps, which indicate geothermal potential.

Other parameters derived from the 3D resistivity voxel model includes 3D surface estimates of the depth to the top of the low resistivity zone, and the depth to the base of the low resistivity zone. See Figs. 15 and 16.

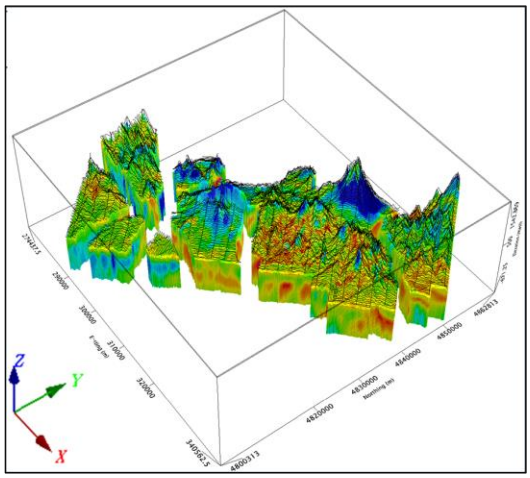


Figure 13: 3D Resistivity Voxel Model

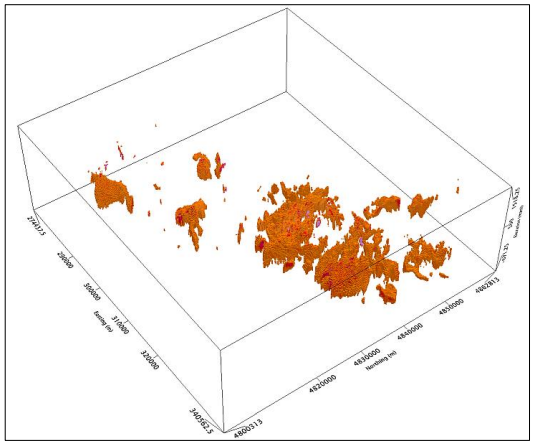


Figure 14: 3D Resistivity Voxel (25 Ωm) Iso-Surface of Interpreted Low Resistivity (Clay-Cap) Zone

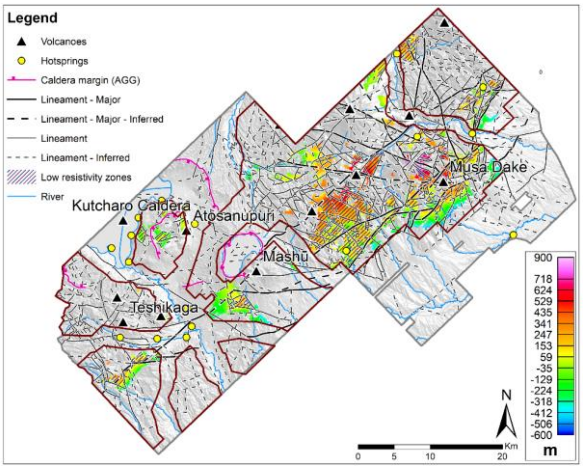


Figure 15: Interpreted Depth of the Top of the Low Resistivity Zone above mean sea level

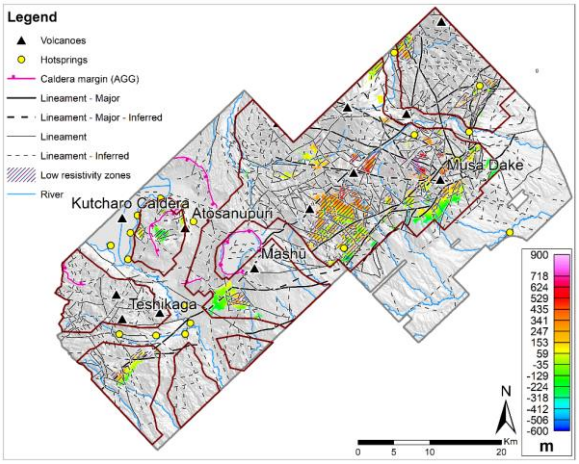


Figure 16: Interpreted Depth of the Base of the Low Resistivity Zone above mean sea level

4.4 Interpreted Implications for Geothermal Prospectivity

The structural interpretation of the Musadake area (NE) of the block shows northeast structures. Major lineaments in the Teshikaga area (W) of the block trend west to west-southwest. These lineaments appear to offset the older northeast trend.

Continuous northwest to north trending structures are important, particularly in the Musadake area, and may represent a conjugate fault system for the dominant northeast faults as a result of northwest compression across the area. Northwest to north trending faults may provide important conduits where the steep faults intersect one another, and where they intersect the northeast-striking faults (e.g. at Musadake volcano).

The timing of volcanism in the Musadake and Teshikaga areas appears directly related to the tectonic age of the mapped lineaments. In the Musadake area, volcanism is generally of Miocene to Pleistocene in age. In the Teshikaga area the volcanism is dated between the Pleistocene and Recent epochs.

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The rhombic shape of the volcanic structures in the Teshikaga area, defined by the lineament interpretation from all datasets, suggests a pull-apart setting.

Once the integrated interpretation of the acquired geophysical datasets was completed, a brief analysis was conducted to identify potentially prospective geothermal areas for further study. The prospective areas identified from the acquired data coincide with low resistivity zones across the Musadake-Teshikaga survey area.

The largest low resistivity zone is in the central-southwest of the Musadake area, marked A on Fig. 17.

Elongate northeast trending low resistivity zones are also present north and south of Musadake (B on Fig. 17) and southwest of Teshikaga (C on Fig. 17). These conductive zones appear to occur along major northeast trending structures through the survey area.

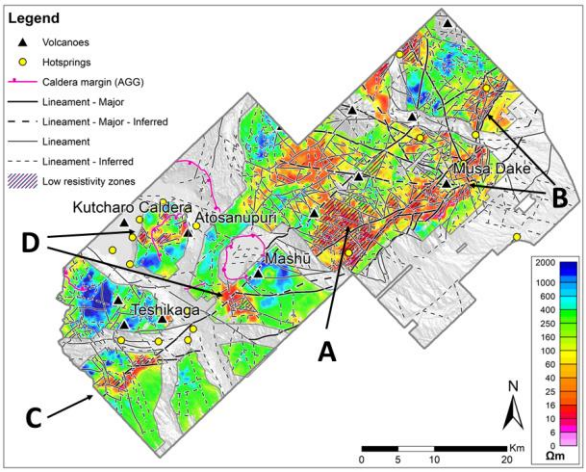


Figure 17: Resistivity Distribution at 100m above mean sea level

Smaller isolated low resistivity zones are present west of the Atosanupuri Volcano and southwest of Maschū Volcano. (D on Fig. 17). Hotsprings and fumaroles are abundant around these lakes, as well as along northeast lineaments interpreted across the survey area.

The low resistivity zones across the area are structurally well-defined in the AGG, magnetic and AEM data. Observed low magnetic intensities in these areas may be related to the conversion and/or destruction of magnetite because of hydrothermal activity.

5. CONCLUSION

HeliFalcon AGG and Helitem AEM technologies have been shown to have the ability to:

- acquire high resolution gravity, resistivity, and magnetic datasets rapidly, and at a consistent and high data density.

- operate in rugged mountainous terrain, and over areas with challenging surface access conditions where ground geophysical surveys are unable to operate efficiently, or at all.

The data acquired in the Musadake-Teshikaga Survey has proven to be of significant value for geothermal exploration and assessment.

Structures identified from AGG data are consistent with the known faults, while abundant additional tectonic and volcanic structure could be mapped in detail. This demonstrates the higher accuracy of the airborne gravity gradiometry data.

Low resistivity zones are generally well constrained by the mapped lineaments, and most are interpreted as zones of hydrothermal alteration and may therefore be prospective. The top of these low resistivity zones could be identified by Resistivity Depth Imaging.

Some low resistivity areas coincide with areas of reduced magnetic susceptibility interpreted to be due to the thermal and alteration effects on magnetite.

Integrated interpretation of multiple datasets reduces ambiguity in geothermal exploration. There is often a good relationship between features mapped from the airborne gravity, resistivity, and magnetic data, as the lithological distribution and alteration is controlled by tectonic and volcanic structures.

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