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Integrated Interpretation of Heliborne AGG and AEM Data for Geothermal Exploration in the Musadake-Teshikaga Area of Japan

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ABSTRACT

An integrated geological interpretation was completed on heliborne multi-physics data for Japan Oil, Gas and Metals National Corporation (JOGMEC) in the Musadake-Teshikaga area, Hokkaido, Japan. HeliFalcon® airborne gravity gradiometer (AGG) and Helitem® airborne electromagnetic (AEM) and magnetic data were acquired and interpreted to aid in the identification of prospective areas for geothermal energy generation.

The interpretation workflow included:

1) Investigation of the regional geologic setting, using publically available data
2) Interpretation of the acquired AGG, AEM and magnetic datasets individually
3) Integration of the AGG, AEM and magnetic interpretations
4) Identification and prioritisation of the prospective geothermal zones

Available geological and published data was also integrated into the geological interpretation. Tectonic and volcanic lineaments were mapped using the AGG, magnetic and AEM data. The AEM data was also used to identify low resistivity zones that potentially correspond with hydrothermal alteration zones.

Northeast lineaments parallel to the Akan-Shiretoko volcanic chain form the most continuous structures in the Musadaka area. These are interpreted to define the Kuril Arc before it was segmented into rotated fault blocks as a result of the collision of this arc with eastern Hokkaido. In the western Teshikaga area, located closer to the Mid Kuril Arc fault, lineaments trending west to west-southwest are more prevalent and offset the older northeast trend. Timing of volcanism in the survey area appears directly related to fault activity. In the Musadake area, volcanism is generally of Miocene to Pleistocene age; in the west, younger Pleistocene to Recent volcanics dominate. The rhombic shape of volcanic structures in the west, defined in the lineament interpretation from all datasets, suggests a hybrid tectono-volcanic origin in a pull-apart setting along the Mid-Kuril Arc fault system.

Low resistivity zones were mapped from the AEM data and appear to correlate with areas that have relatively low magnetic amplitudes. This suggests possible magnetite destruction and demagnetization related to thermal or hydrothermal activity. Low resistivity zones are more pronounced and common in the eastern Musadake area. The low resistivity zones and low magnetic amplitude anomalies appear structurally well-defined in the geophysical datasets. These prospective zones are subject to more focused geothermal exploration.

1. INTRODUCTION

In 2012, JOGMEC began a series of multi-physics acquisition programs over areas of known and potential interest for geothermal exploration throughout Japan. Steep terrain over large portions of the survey areas resulted in the selection of a rotary-wing platform for data acquisition. The project had two key objectives from the beginning: evaluate the effectiveness of heliborne geophysical data for geothermal exploration, and identify new areas of geothermal potential. As part of this ongoing program, 9,932 line-km of AGG data and 5,567 line-km of AEM and magnetic data were acquired in 2015 and 2016 across the Musadake-Teshikaga area in eastern Hokkaido (Figure 1).

This paper discusses briefly the workflow and results of an integrated interpretation of the newly acquired geophysical datasets. While the interpretation is based primarily on the heliborne AGG, AEM and magnetic datasets acquired in Musadake-Teshikaga, it also incorporates other sources of publically available information, including geological maps, scientific literature and reports, remote sensing data, etc. The main objective of the integrated interpretation presented herein is to illustrate how airborne datasets may be useful tools for identifying potential structural and lithological features of significance for geothermal exploration. Further work was carried out, in part using the results of this integrated interpretation, by Sumiko Resources Exploration & Development (SRED) for JOGMEC to assist in ongoing geothermal exploration in the area.

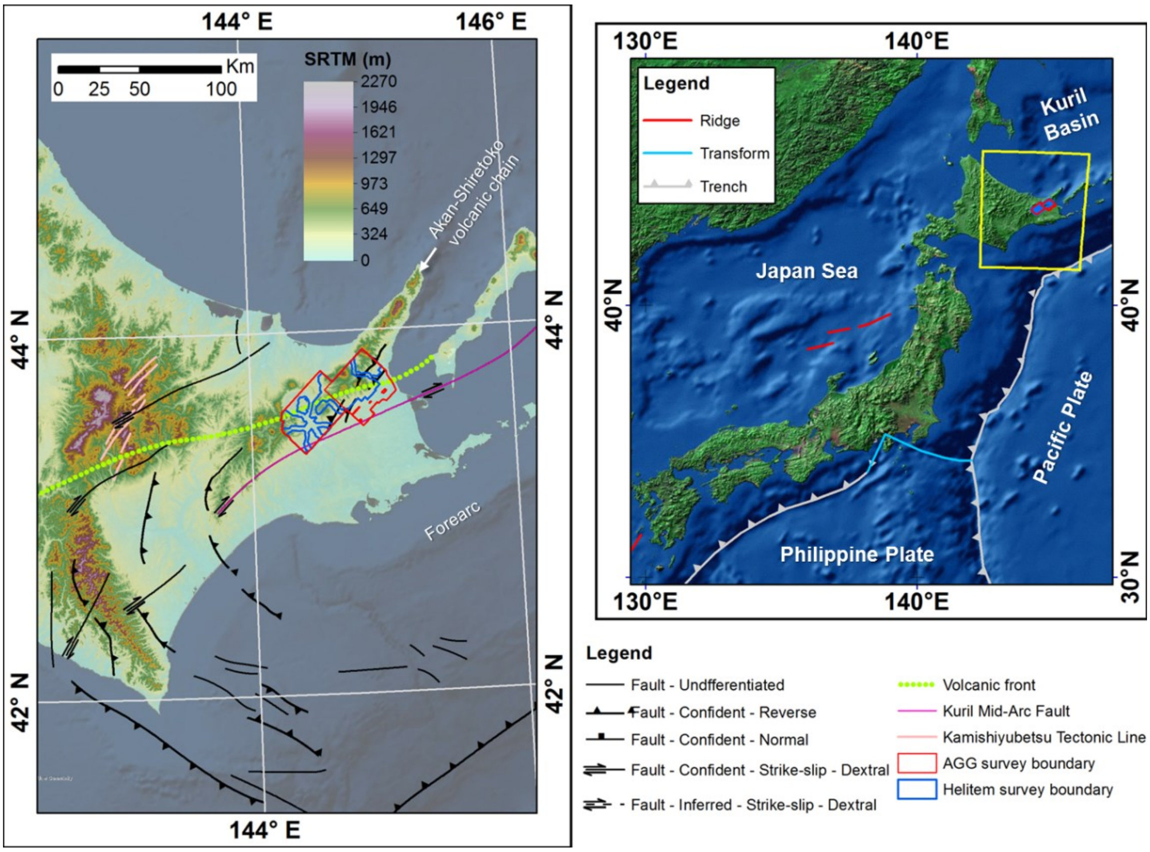

Figure 1: The Musadake-Teshikaga heliborne survey is located in eastern Hokkaido. The survey area is north of the Kuril Mid-Arc fault, and east of the Kamishiyubetsu Tectonic Line. The survey data includes both AGG (outlined in red) and Helitem AEM and magnetic (outlined in blue) data, and was acquired in 2015 and 2016. Line spacing for the Musadake-Teshikaga survey data was 250 m.

2. REGIONAL GEOLOGICAL SETTING

Hokkaido occurs at the juncture of the north-trending Northeast Japan arc, resulting from the Late Jurassic to Early Cretaceous collision of the Eurasian and North American plates, and the active southern end of the Kuril arc. The Musadake-Teshikaga survey area covers part of the Akan-Shiretoko volcanic chain in eastern Hokkaido, a segment of the Kuril volcanic arc that consists mainly of nine subareal andesitic stratovolcanoes and three calderas (Goto et al., 2001).

The presumed former east-dipping Northeast Japan subduction zone is thought to be the located in the Cretaceous-Middle Eocene Susanai-Kamuikotan metamorphic belt, which extends through Hokkaido into Sakhalin to the north (Kimura et al, 2014; Zharov, 2005). Basement rocks underlying the Musadake-Teshikaga survey area form part of the Nemuro Belt, and are presumed metamorphic in composition, but these rocks have not been extensively studied and basement composition is therefore largely unknown.

The current west-northwest subduction along the northeast trending Kuril arc, which started after the Middle Miocene (Jolivet and Huchon, 1989), results in an oblique collision between the Kuril fore-arc and the Northeast Japan fore-arc (Jolivet, 1986; Kimura, 1996). After examining the horizontal slip directions obtained from shallow thrust earthquakes, DeMets (1992) concluded that these demonstrate strain convergence is partitioned into less oblique subduction closer to the trench and results in trench-parallel displacement of fore-arc slivers. The Kuril Mid-Arc Fault (Schnürle et al., 1995), south of the survey area (purple line, Figure 1), is a major trench-parallel strike-slip fault. The Kamishiyubetsu Tectonic Line (pink lines, Figure 1) to the west, is a major northeast trending deformation zone that developed as a result of this oblique collision (Kimura, 1986; Jolivet and Huchon, 1989).

3. 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. The 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, prospective zones for further geothermal exploration were derived from the integrated interpretation of the combined airborne datasets.

3.1 Interpretation Process

After investigation of the regional geological and tectonic setting for the survey area, structural features were mapped for each of the individual datasets (Figure 2). Tectonic and volcanic features were mapped initially as lineaments, and attributed in ArcGIS according to their perceived importance (major or minor features) and the level of confidence with which they could be mapped (i.e. confident or inferred). The structural interpretations for the individual datasets were then combined, integrated and attributed according to the data sources (AGG, magnetic, and EM) on which the features were mapped. Commonly, small positional variations were noted between lineaments mapped from the AGG, magnetic and/or AEM data. These positional variations were attributed to differences in depth at which the respective lateral variations in rock property (density, susceptibility and/or resistivity) are imaged as well as geological factors such as fault dip.

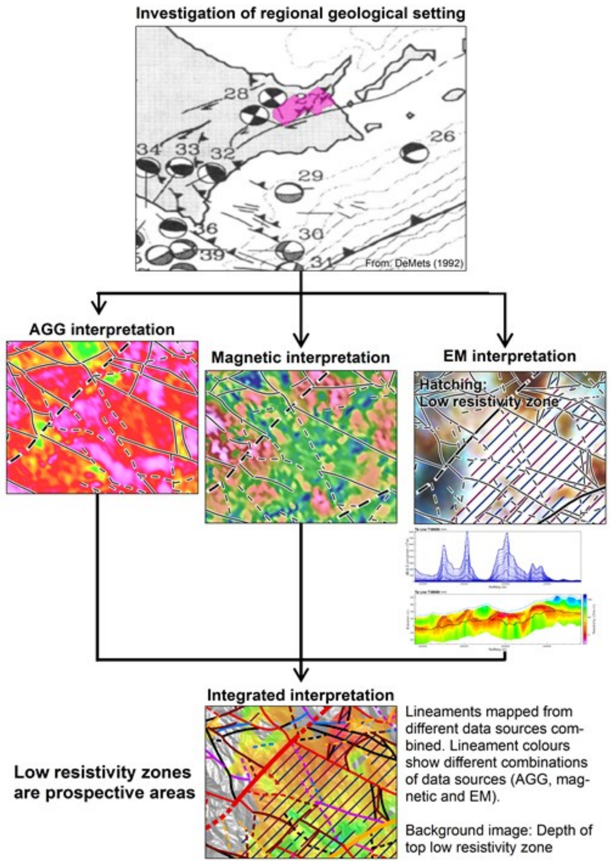

Figure 2: Generalised interpretation workflow.

The low resistivity zones were initially mapped from the AEM dB/dt Z component ternary image. The ternary image is a composite RGB (red green blue) image that combines late (channel 24; red), mid (channel 15; green) and early off-time (channel 06; blue) channels. Areas coloured white on the resultant image indicate conductive rocks while darker shaded areas are indicative of resistive rocks. The Z, or vertical, dB/dt component images the AEM response of horizontal structures best, and shows the rate of change of the vertical component of the secondary AEM signal with time.

To gain a better understanding of the 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, or RDIs, were generated for all survey lines. These were used to generate both resistivity voxel models and resistivity depth slices for the survey area. The RDI profiles were also used to derive a top of low resistivity zone horizon, to better image the 3D geometry of the low resistivity zones across the survey area.

Figure 3 shows the resulting map-based integrated interpretation.

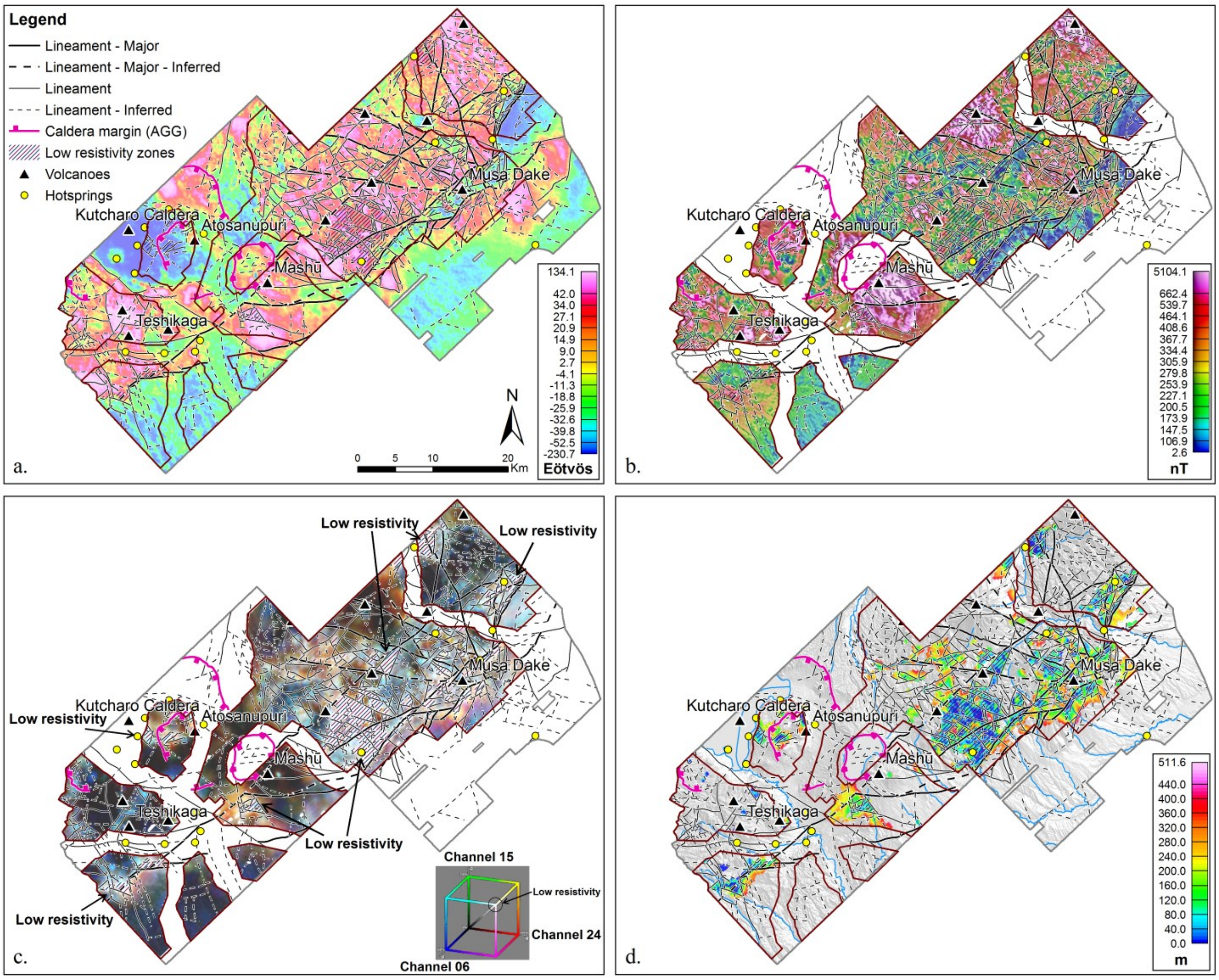

Figure 3: The final airborne integrated interpretation overlain on a. the AGG data (G_{DD}, or vertical gravity gradient component); b. the magnetic data (semi-transparent colour image is the MAMFV, or Magnitude of the Anomalous Magnetic Field Vector image, and is plotted over a greyscale image of the first vertical derivative of the MAMFV); c. the AEM data (dB/dt Z component ternary, using channels 24, 15 and 6); and d. Coloured image shows the top of low resistivity zone (in meters below ground) interpreted from the resistivity depth images (RDIs) plotted on the greyscale sun-shaded digital terrain model. Rivers are shown in blue.

3.2 Interpretation Results and implications for geothermal prospectivity

The structural interpretation of the eastern Musadake block (Figure 4) shows dominant northeast structures that comprise a fault-bounded anticlinorium along which the Akan-Shiretoko volcanic chain formed. In contrast, major lineaments in the western Teshikaga block trend west to west-southwest, related to the Kuril Mid-Arc Fault. These lineaments appear to offset the older northeast trend.

Continuous northwest to north trending structures are important, particularly in the eastern Musadake block. These structures 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 survey 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.

The rhombic shape of the volcanic structures in the Teshikaga area, defined by the lineament interpretation from all datasets, suggests a hybrid tectono-volcanic origin in a pull-apart setting during activity of the Kuril Mid-Arc Fault.

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

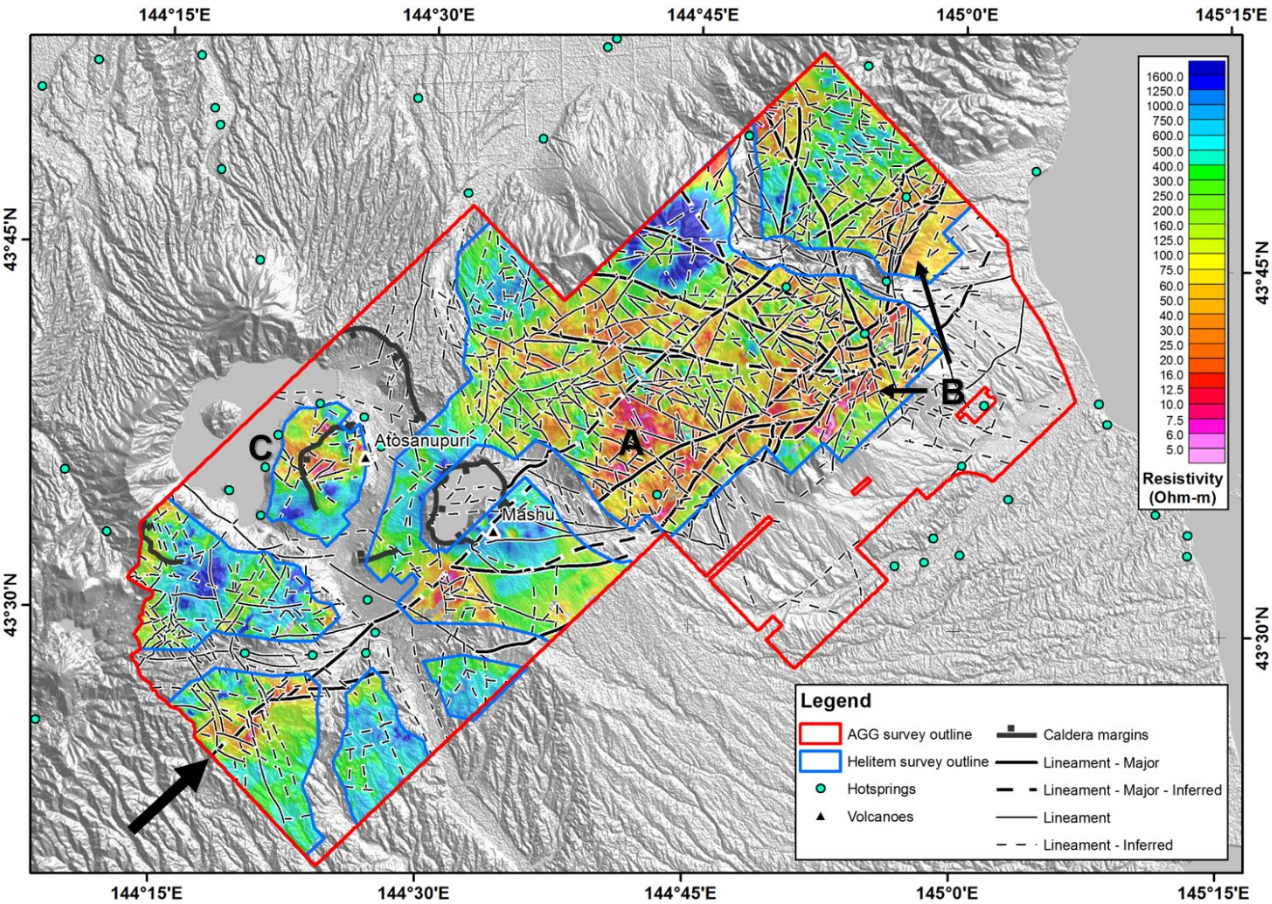

Figure 4: The final airborne integrated interpretation plotted on a resistivity depth slice extracted from the resistivity voxel model at 200m below ground surface. Background shows the greyscale sun-shaded digital terrain model.

The largest low resistivity zone is located in the central-southwest of the Musadake survey block (Figure 4, label A).

Elongate northeast trending low resistivity zones are also present in the south of the Musadake survey block (Figure 4, B) and in the west of the Teshikaga survey block (thick black arrow, Figure 4). These conductive zones appear to occur along major northeast trending structures through the survey area.

Elsewhere in the Teshikaga block, smaller isolated low resistivity zones are present west of the Atosanupuri Volcano (Figure 4, C; southeast of Lake Kutcharo) and southwest of Maschū Volcano. 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 on the reduced to pole magnetic image in these areas may be related to the conversion and/or destruction of magnetite as a result of thermal and/or hydrothermal activity.

4. CONCLUSIONS

The integrated interpretation of HeliFalcon AGG, and Helitem AEM and magnetic data in the Musadake-Teshikaga area focused on identifying key tectonic and volcanic lineaments in the area as well as potential zones of hydrothermal alteration.

Lineaments were interpreted individually from each of the datasets, and attributed according to the data source (AGG, magnetic, and/or EM); the feature's importance (major or minor); and the certainty with which it could be interpreted (confident or inferred). Low resistivity zones mapped in areas of favourable geothermal prospectivity were commonly observed to coincide with zones of reduced magnetic susceptibility. This is interpreted to result from the thermal and alteration effects on magnetite.

Based on the heliborne data interpretation, the most prospective areas occur along the southernmost parts of the major northeast trending faults in the west of the Musadake survey block. In the Teshikaga survey block smaller scale prospective zones are present near the Atosanupuri and Maschū volcanoes.

The results and products of the integrated interpretation of the AGG and AEM data presented herein have been used in combination with available geological and geophysical data for additional geothermal exploration work, including inversions of the potential field data to better constrain rock property distribution with depth, and fieldwork to both ground-truth the interpretation results and assist in delineating geothermal drillhole targets (Ishikawa et al, submitted).

5. ACKNOWLEDGEMENTS

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REFERENCES

DeMets, C.: Oblique Convergence and Deformation Along the Kuril and Japan Trenches, *Journal of Geophysical Research*, ***97***, (1992), 17,615-17,625.

Goto, Y., Funayama, A., Gouchi, N. and Itaya, T.: K-Ar ages of the Akan-Shiretoko volcanic chain lying oblique to the Kurile trench: Implications for tectonic control of volcanism, *Island Arc*, ***9***, (2001), 204-218.

Ishikawa, H., Nogami, S., Endo, M., Feijth, J., Hope, J., Mouri, T. and Nakamoto, G.: Targeting geothermal exploration using airborne multi-geophysics, *NRR Special Issue of ISME-XV*, submitted.

Jolivet, L.: American-Eurasia plate boundary in eastern Asia and the opening of marinal seas, *Earth and Planetary Science Letters,* ***81***, (1986), 282-288.

Jolivet, L. and Huchon, P.: Crustal-scale strike-slip deformation in Hokkaido, northern Japan, *Journal of Structural Geology*, ***11***, (1989), 509-522.

Kimura, G.: Oblique subduction and collision: forearc tectonics of the Kuril arc, *Geology*, ***14***, (1986), 404-407.

Kimura, G.: Collision orogeny at arc-arc junctions in the Japanese Islands, *Island Arc*, ***5***, (1996), 262-275.

Kimura, G., Hashimoto, Y., Kitamura, Y., Yamaguchi, A. and Koge, H.: Middle Miocene swift migration of the TTT triple junction and rapid crustal growth in southwest Japan: A review, *Tectonics*, ***33***, (2014), 1219-1238.

Schnürle, P., Lallemand, S.E., von Huene, R. and Klaesschen, D.: Tectonic regime of the southern Kurile Trench as revealed by multichannel seismic lines, *Tectonophysics*, ***241***, (1995), 259-277.

Zharov, A.E.: 2005, South Sakhalin tectonics and geodynamics: A model for the Cretaceous-Paleogene accretion of the East Asian continental margin, *Russ.J.Earth Sci.*, ***7***, (2005), 1-31.