High-Resolution Unmanned Aerial Vehicle Aeromagnetic Surveys for Mineral Exploration Targets

C. Walter^{*}, A. Braun, and G. Fotopoulos

*Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, K7L 3N6, Ontario, Canada.
Emails: callum.walter@queensu.ca; braun@queensu.ca; georgia.fotopoulos@queensu.ca*

** Author to whom correspondence should be addressed: Callum.walter@queensu.ca*

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ABSTRACT

Recent advancements in geophysical exploration have been realized through reliably integrating unmanned aerial vehicle platforms with lightweight, high-resolution magnetometer payloads.

Unmanned aerial vehicle aeromagnetic surveys can provide a contemporary data product between the two end-members of coverage and resolution attained using manned airborne and terrestrial magnetic surveys. This new data product is achievable because unmanned aerial vehicle platforms can safely traverse with magnetometer payloads at flight elevations closer to ground targets than manned airborne surveys, while also delivering an increased coverage rate compared to walking conventional terrestrial surveys. This is a promising new development for geophysical and mineral exploration applications, especially in variable terrains. A three-dimensional unmanned aerial vehicle aeromagnetic survey was conducted within the Shebandowan Greenstone Belt, northwest of Thunder Bay, Ontario, Canada, in July 2017. A series of two-dimensional grids (~500 m x 700 m) were flown at approximate elevations of 35 m, 45 m and 70 m above ground level using a Dà-Jiāng Innovations multi-rotor unmanned aerial vehicle (S900) and a GEM Systems, Inc. Potassium Vapour Magnetometer (GSMP-35U). In total, over 48 line-km's of unmanned aerial vehicle aeromagnetic data were flown with a line spacing of 25 m. The collected aeromagnetic data were compared to a regional heliborne aeromagnetic survey flown at an elevation of approximately 85 m above the terrain, with a line spacing of 100 m, as well as a follow-up terrestrial magnetic survey. The first

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vertical derivative of the gathered unmanned aerial vehicle total magnetic field data was calculated both directly between each of the different flight elevations, and indirectly by calculating the values predicted using upward continuation. This case study demonstrates that low flight elevation unmanned aerial vehicle aeromagnetic surveys can reliably collect industry standard total magnetic field measurements at an increased resolution when compared to manned airborne magnetic surveys. The enhanced interpretation potential provided by this approach also aided in delineating structural controls and hydrothermal fluid migration pathways (a pair of adjacent shear zones) related to gold mineralization on site. These structural features were not clearly resolved in the regional manned airborne magnetic data alone, further demonstrating the utility of applying high-resolution unmanned aerial vehicle aeromagnetic surveys to mineral exploration applications. The conclusions and interpretations drawn from the unmanned aerial vehicle aeromagnetic data, coupled with historical data, were applied to make a new gold mineralization discovery on the site, assayed at 15.7 g/t.

INTRODUCTION

Magnetic surveys applied in the mineral exploration industry passively sense the total magnetic intensity (TMI) of an area of interest and are regarded as one of the most cost effective and widely used methods for discovering and delineating potential economic mineral deposits (Airo 2015). The traditional exploration platforms used to collect total magnetic field data include high coverage, but low resolution manned airborne surveys, and high resolution, but low coverage terrestrial surveys (Everett 2013). Since the second world war, there have been relatively few innovative advancements with respect to these magnetic exploration platforms, as ships, manned aircraft, and terrestrial vehicles were all used for magnetometry. The surveying design parameters of these traditional platforms have also remained fixed due to their physical constraints to a 2-D surveying space, where manned aircraft survey at one flight elevation above the ground (~100 m) and terrestrial surveys take place on the ground. This results in both traditional surveying platforms providing unique magnetic data products at opposite ends of the resolution and coverage spectrum that do not overlap. Newly proven unmanned aerial vehicle (UAV) aeromagnetic surveys have the potential to bridge these gaps in both

resolution and coverage, while also increasing the safety of surveying personnel and providing a more economically viable solution within a diverse market.

Within the past decade, the development of UAV-borne aeromagnetic surveys has demonstrated a higher rate of coverage than terrestrial magnetic surveys, ie. at speeds of 10 m/s (Cunningham 2016), while also providing a higher resolution than manned airborne surveys, ie. <35 m from the target surface (Walter et al. 2019), as depicted in Figure 1. This new spatial and temporal scale can provide a contemporary data product between the existing two end-members of coverage and resolution in current magnetic surveys, especially for smaller to medium scale projects on the order of 1 – 10's km².

Instances where magnetometer payloads have been integrated with a UAV platform are shown in the studies of: (Parvar 2016; Wood 2016; Malehmir et al. 2017; Walter et al. 2017; Cunningham et al. 2018; Parvar et al. 2018; and Walter et al. 2019). However, there are limited case studies published to date that directly compare the resolution capabilities between manned airborne, UAV-borne and terrestrial magnetic data over a known mineral exploration target. Within this realization, a UAV-borne aeromagnetic case study was flown to quantify and assess the achievable resolution and data quality at different flight elevations, comparing these with a regional scale, manned heliborne aeromagnetic survey previously flown over the same site. An additional terrestrial magnetic survey was conducted to verify and ground truth the magnetic features sensed by the UAV-borne aeromagnetic survey. Herein, the surveying methodology, logistics and gathered UAV-borne aeromagnetic data are discussed to outline the potential benefits and applications of conducting low flight elevation, high-resolution, UAV-borne aeromagnetic surveys.

FIELD SITE

Geology of the Survey Area

The UAV-borne aeromagnetic survey was conducted throughout the week of July 10 to 14, 2017, 120 km Northwest of Thunder Bay, Ontario, Canada. The survey area, shown with a purple outline in Figure 2, is located approximately 1 km west of Moss Lake, hosted within the Shebandowan

Greenstone Belt and separated from the Quatico Subprovince (metasedimentary belt) to the North by the Boundary Fault Zone (Chorlton 1987; Osmani 1993). The dominant geologic units within the survey area include: intermediate to mafic metavolcanic rocks, intermediate to felsic metavolcanic rocks, chemical metasedimentary rocks (banded iron formation), clastic metasedimentary rocks and mafic to ultramafic intrusive rocks. On a regional scale, the steeply dipping ($>75^\circ$) metamorphosed geologic units of the Shebandowan Greenstone Belt and the Quatico Metasedimentary Belt dominantly strike Northeast-Southwest ($40^\circ/220^\circ$), as described by (Osmani 1997). Regional and local scale shear zones a part of the Shebandowan Greenstone Belt also dominantly strike approximately ($40^\circ/220^\circ$). A secondary set of shear zones is known to crosscut this dominant structural trend within the area. These secondary shear zones range in their orientation, striking between approximately East-West ($90^\circ/270^\circ$) to Southeast-Northwest ($135^\circ/305^\circ$). Late intrusive rocks within the Shebandowan Greenstone Belt are felsic to mafic in composition, with an example being the stock of granite-syenite surrounding Moss Lake in the Northeast.

The Shebandowan Greenstone Belt exhibits numerous occurrences of gold and silver mineralization which are dominantly hosted in vein/replacement type deposits, closely related to primary and secondary structural trends. The area of interest occurs within the Huronian Gold Project, a mineral exploration target presently owned by Kesselrun Resources Ltd. Previous mining operations on this site were conducted under the names of Kerry, Moss and Ardeen Mines, as well as many other smaller ventures since 1871 when gold was first discovered on the site (Watson 1929; Harris 1970). Extensive exploration and mining activities have been conducted surrounding the Moss Lake area since the 1930's, when industrialized production of the site began. The previous mineralization occurred within a gold bearing quartz vein hosted by a heavily sheared zone of intermediate to mafic metavolcanic rocks (Harris 1970; Chorlton 1987). In general, the quartz vein is parallel to the structure of the shear zone and the schistosity of the altered intermediate to mafic metavolcanics (chlorite schist). The vein is not continuous, but forms lenses within the shear zone, from ~ 1 - 60 m long that are arranged in an en echelon manner with ends over lapping (Harris 1970). The strike length of the mined auriferous vein system extended laterally for ~ 750 m and extend vertically down

to depths of ~375 m in the mine workings. The approximate gold grade of the mined ore ranged between 1.7 g/t to 5.5 g/t according to compiled assays in Harris (1970).

Regional Aeromagnetic Data

A regional aeromagnetic survey was conducted in 2004 by Geotech Ltd. throughout the western extent of the Shebandowan Greenstone Belt for the Ontario Geological Survey. The data were published as part of the Ontario Geological Survey– Geophysical Data Set 1241 (Ontario Geological Survey 2014). A 4 km x 4 km gridded section of the residual magnetic field data is presented in Figure 3. The Northeast-Southwest trend of warmer colors, with a positive residual magnetic field intensity (RMI), approximately outlines the extent of the mafic and ultramafic metavolcanic units within the Shebandowan Greenstone Belt. The northern section of negative RMI values is due to the sharp transition into the Quatico Metasedimentary Belt, crossing the Boundary Shear Zone. The southern section of negative residual field values is due to a transition into the intermediate to felsic metavolcanic rocks, a part of the Shebandowan Greenstone Belt. The dominant positive RMI feature within the Moss Lake area is a discontinuous banded iron formation (BIF) observed extending from approximately (0 m E, 1000 m N) in the southwest to (3000 m E, 4000 m N) in the Northeast. The extent of the UAV-borne aeromagnetic survey (outlined in purple) is located north and west of the iron formation, targeting a relatively lower amplitude, positive RMI anomaly trend also striking approximately (40°/220°). This magnetic anomaly trend occurs adjacent and parallel to the known gold mineralization zone. Resolving this magnetic feature at a higher resolution aids in better understanding the primary and secondary structural controls of mineralization on site.

The magnetic sensor used throughout the regional-scale heliborne survey was a cesium vapour optically pumped magnetometer which provided a sampling frequency of 10 Hz and a sensitivity of 0.02 nT (Ontario Geological Survey, 2014). The magnetometer used in the heliborne aeromagnetic survey and the UAV-borne aeromagnetic survey (a potassium vapour magnetometer) are both optically pumped vapour magnetometers, providing similar specifications and limiting variability when comparing measurements between the two data sets. The helicopter platform flew over the area of interest at approximately 100 m flight elevation (standard deviation of 6.5 m) with the

magnetometer suspended 15 m below the aircraft, making the nominal flight elevation of the magnetometer approximately 85 m AGL. The flight lines of the survey were conducted perpendicular (310°/130°) to the dominant regional trend in the area. The flight speed of the helicopter was approximately 30 m/s, which provided a sampling interval of approximately 3 meters along the survey lines. The survey was conducted with a line spacing of 100 m and no tie lines where flown over the 500 m x 700 m UAV-borne aeromagnetic surveying area (Ontario Geological Survey, 2014).

MATERIALS, METHODS & SURVEY DESIGN

Unmanned Aerial Vehicle Platform & Survey Parameters

The platform used for the UAV-borne aeromagnetic survey was a DJI S900 multi-rotor UAV, as shown in Figure 4. It was equipped with an A2 flight controller and compatible with the DJI Ground Station 4.1 software, allowing for flight lines to be planned prior to take-off at the ground station. The pre-programmed flights were conducted at a speed of ~7.5 m/s along ~700 m long lines. Three individual grids (~500 m x 700 m) of magnetic data were flown at elevations of 70 m, 45 m, and 35 m AGL. Twenty parallel survey lines trending North - South were flown with an approximate 25 m line separation at each elevation. The survey lines were flown in an approximate (0°/180°) orientation attempting to resolve secondary structural features to the main regional trend (40°/220°), suspected by the property owners and mentioned in (Chorlton 1987; Osmani 1997) to be striking approximately (90°/270°) in the area.

Five individual flights were required per elevation level to gather the TMI data, totalling fifteen flights for all three elevations. In addition, two flights were required to gather the tie lines at the lowest flight elevation of 35 m using a line spacing of 50 m. The standard deviation of the flight elevations ranged from approximately 2 to 2.5 m depending on the wind conditions. This included whether the UAV was flying upwind, downwind or through a crosswind. The UAV flight elevation was independently verified with an onboard GPS and with laser altimeter measurements during the takeoff and landing maneuvers over flat ground. Overall, the flight endurance of the UAV was

approximately twelve minutes, using a 10,000 mAh battery and approximately fifteen minutes, using a 16,000 mAh battery. In total, over 48 line-km of data were collected within a 7-hour period.

Potassium Vapour Magnetometer & Payload

The magnetic sensor used during surveying was a GEM Systems Inc. GSMP-35U potassium vapour magnetometer composed of an electrical console and magnetometer sensor. The magnetometer electrical console was balanced and rigidly secured directly to the frame of the multi-rotor UAV. The magnetometer sensor head was semi-rigidly mounted to the UAV, as described in (Walter et al. 2019), and suspended 3 m below the airframe. The semi-rigid mount ensures that the yaw axis of the magnetometer is rigidly fixed to the yaw axis of the UAV in flight, aiding in magnetometer stability. The semi-rigid mount also preserves the rotation independence between the pitch and roll axes of the magnetometer and UAV, protecting the flight stability and efficiency of the UAV. Previous studies such as (Wells 2008; Forrester 2011; Cunningham 2016; Parvar 2016; and Tuck et al. 2018) have investigated the magnetic signals produced by various UAVs and provide guidelines and considerations for sensor placement. Studies such as (Parvar 2016; Malehmir et al. 2017; Walter et al. 2017; Parvar et al. 2018; and Walter et al. 2019) have all concluded that minimal platform magnetic signal interference occurs when a GSMP-35U potassium vapour magnetometer is suspended at or greater than 3 m below a DJI S900 multi-rotor UAV. To build upon these generic offset distance guidelines, a refined methodology was applied to specifically quantify the magnetometer offset distance at which the magnetic interference signals generated by the DJI-S900 multirotor UAV attenuated below the GSMP-35U magnetometers resolution threshold.

This methodology involved conducting background magnetic field noise tests with the GSMP-35U in a fixed position and away from sources of magnetic interference. These measurements consistently demonstrated that the achieved resolvability threshold of the GSMP-35U in the field setting was approximately 0.014 nT, Root Mean Square Deviation (RMSD) at 10Hz. This achieved resolvability is an order of magnitude less sensitive than the manufacture's datasheet sensitivity

specification of 0.3 pT/Hz (0.003 nT at 10Hz). Multiple offset tests conducted using this methodology determined that the magnetic interference signal generated by the DJI-S900, hovering with a simulated 2.2 kg magnetometer payload, had sufficiently attenuated below the measured resolution threshold of the GSMP-35U (0.014 nT) at 3 m. Therefore, the magnetometer was suspended at this established offset distance of 3 m and an RMI correction used specifically for the UAVs magnetic interference signal was not required. If the magnetometer was placed closer to the UAV and within the determined offset distance (within the magnetometers resolvability threshold of 0.014 nT) a magnetic compensation methodology would have had to be applied to correct for the permanent, induced and eddy current components of the magnetic interference generated by the UAV. It is important to note that this offset distance is only valid for the DJI-S900 and the GSMP-35U magnetometer combination with a 2.2 kg payload, as other platform and sensor combinations must be assessed prior to the survey to determine their minimum offset distance.

In addition to the main magnetometer payload, a data acquisition system was incorporated to collect and store the magnetic field and positional measurements. The data acquisition system included a real-time, single-frequency (L1) GPS receiver (U-blox EVK – 7), laser altimeter (Lightware SF-11), on-board computer (Raspberry Pi 2) and external 5 V battery pack. In total, the combined magnetometer payload, specialized mount and data acquisition system weighed 2.2 kg. Most of the payload weight (~1.5 kg) is accounted for by the magnetometer and electrical cabling. All on-board sensors collected data at or above 10 Hz resulting in an observation density of over one point per meter along survey lines. A base station magnetometer (GEM Systems Inc. GSM-19T) was set up in a magnetically quiet location, to measure the diurnal variations of the Earth's magnetic field. Following acquisition, the magnetic data were processed to calculate the residual magnetic field and first vertical derivative.

To keep the optically pumped magnetometer correctly oriented with respect to the Earth's magnetic field vector (Inclination: 74° N, Declination: 2.5° W) at the surveying site (International Geomagnetic Reference Field 2017) and to ensure that continuous magnetic measurements were collected, the procedure and conclusions outlined in (Walter et al. 2019) was applied. This resulted in

~95% of the collected magnetic data points being locked and within the industry standard 4th difference cut-off of ± 0.05 nT (Coyle et al., 2014).

Conditions in the Survey Area

The Moss Lake area is densely vegetated being on the southern edge of the boreal forest, with the tallest trees in the area reaching approximately 20 m – 25 m AGL. A minimum flight elevation of 35 m for the magnetometer was maintained to ensure these naturally occurring obstructions were avoided. Topography of the site is typical of shield terrain and includes steep cliffs, broad hills and elongated valleys filled with flowing and/or standing bodies of water. The topographic relief in the area ranged from approximately 435 m to 475 m above sea level (ASL). The end of the access road to the survey area culminated in a trench off area (~15 m x 30 m) on top of a ridge acting as an ideal take-off and landing location from which to conduct flight operations. The relatively high elevation of this point, coupled with the lack of vegetation on the horizon, allowed for a visual line-of-sight to be maintained out to approximately 700 m to the North. Keeping the UAV within a visual line-of-sight in densely forested and remote areas is presently one of the major regulatory challenges and limitations hindering these types of non-invasive operations within Canada.

Weather conditions on the principal surveying day (July 14, 2017) were calm, warm, and sunny, transitioning into an overcast sky with a gradual westerly wind throughout the day. Historical weather data gathered at the Thunder Bay International Airport (Government of Canada 2018) recorded an average wind speed of 3.5 m/s from the West, with gusts up to 5 m/s on July 14, 2017.

Follow-up Terrestrial Magnetic Survey and Site Conditions

A terrestrial magnetic survey was conducted in early April 2019 to compare with the previously flown manned airborne and UAV-borne aeromagnetic data. A diagram comparing the relative elevations above the ground for each of the five magnetic surveys is presented in Figure 5. A GEM Systems Inc. GSM-19T walking magnetometer, with an absolute accuracy of ± 0.2 nT was used to conduct the survey, while a second GSM-19T was used as a base station. The terrestrial magnetic survey took

place in early April so that the various marshes, swamps and standing bodies of water, accounting for approximately 50% of the landcover on site, would be frozen and snow covered. This allowed the water bodies of the site to be traversed with relative ease by the operators. Cut survey lines were not provided, so accessing the site during a time of limited vegetation growth and without swarming insects was another benefit. Even with the benefits of conducting the survey during this time of the year, there were numerous steep cliff faces running parallel to the dominant structural trend which prevent the use of properly spaced grid lines and resulted in a wondering traverse throughout most of the surveying area.

Site conditions throughout the two weeks of terrestrial surveying (April 1 – 14, 2019) varied drastically day to day. Original ground conditions saw 1 m of snowpack with an icy cap layer that allowed for ideal surveying conditions when temperature remained around $-10\text{ }^{\circ}\text{C}$. Operators during these times could remain on top of the snowpack and traverse with relative ease over the frozen water bodies. A warm front ($10\text{ }^{\circ}\text{C}$) with heavy rain moved through the area towards the end of the first week and drastically changed site conditions. Due to this warm front, snowpack no longer held operators' weight and most frozen low-lying areas began to fill with runoff and melt water, effectively ceasing terrestrial operations over a large area of the site. Overall, the varying terrain, steep cliffs, lack of cut lines, dense vegetation, unfavourable weather conditions and need to circumnavigate numerous water bodies made it a challenge to plan and conduct the terrestrial magnetic survey. This type of terrain and surveying conditions exemplify where UAV-borne aeromagnetic surveys can provide a superior logistical advantage for exploration projects.

RESULTS

Unmanned Aerial Vehicle Total Magnetic Intensity Data Quality

Throughout the UAV-borne aeromagnetic survey, a DJI S900 multi-rotor UAV, a magnetometer suspension length of 3 m below the platform, and a total payload weight of 2.2 kg were used. For these surveying parameters, the electromagnetic interference generated by the UAV was not sensed by the suspended magnetometer throughout all flight maneuvers, as the magnetic field produced by

the UAV had sufficiently attenuated below the achieved resolution threshold of the GSMP-35U magnetometer, measured to be 0.014 nT during background magnetic field noise tests prior to the survey. This is demonstrated within a profile of the gathered TMI data as shown in Figure 6, where high frequency TMI variations are not present in either the flight lines or the corners. The calculated fourth difference of the TMI also demonstrates a low overall noise level in the collected data, where all values are within the ± 0.05 nT industry standard cut-off (green rectangle) (Coyle et al. 2014).

Unmanned Aerial Vehicle Residual Magnetic Intensity Data

Residual magnetic intensity maps of the Moss Lake area were produced for the manned airborne flight elevation of 85 m and the three UAV flight elevations of 70 m, 45 m and 35 m. These respective aeromagnetic maps are shown in Figures 7 (a), (b), (c), and (d), presented in local grid coordinates, where (0 m E, 0 m N) corresponds to NAD 83 UTM Zone 15 U, coordinates of (664200 m E, 5378600 m N). The colorscale range is identical in all maps to highlight the changes in resolution and sensitivity between each flight elevation. The flight lines for each survey are plotted using dots with a red center and black outline. The magnetic feature targeted from the regional heliborne aeromagnetic map was a broad, positive magnetic anomaly striking approximately $40^{\circ}/220^{\circ}$, as shown in Figure 7(a). The larger, positive amplitude magnetic signal located in the lower Southeast corner of the study area is due to a section of the banded iron formation and was not the target of this survey. The residual amplitude of the main targeted anomaly sensed during the 85 m flight elevation was approximately 425 nT. When comparing this to the spatially corresponding magnetic signature sensed at the flight elevations of 70 m, 45 m and 35 m, there was an RMI amplitude increase to approximately 450 nT, 600 nT, and 725 nT, for each respective decrease in flight elevation.

The 45 m and 35 m UAV-borne RMI maps (Figures 7(c) and 7(d)) were able to resolve two distinct positive RMI anomaly trends separated by a relatively negative trend in between. The more northern RMI trend extends throughout the entire map area, while the second adjacent, positive RMI trend, located approximately 200 m south of the first, attenuates around (200 m E, 200 m N). This contrasts the magnetic data sensed at the 85 m and 70 m flight elevations, where the observed

magnetic signal amplitude is reduced, and the anomaly shapes have broadened such that the two independent anomaly peaks are fused together. The resolution of the magnetic data collected at these higher elevations (both the 25 m line spacing UAV-borne data and the 100 m line spacing heliborne data) makes a precise interpretation of the anomaly(ies) more uncertain. Hence, gathering UAV-borne aeromagnetic data closer to targets increased the resolution and amplitude of the measured magnetic field values, leading to higher-quality data products and allowing for improved interpretations.

Geologic, Topographic and Optical Data

Additional data from the 500 m x 700 m UAV-borne magnetic survey area were compiled including simplified local geology, a digital elevation model (DEM) and satellite imagery. The simplified local geology, modified after (Osmani 1997), is presented in Figure 8, showing intermediate to mafic metavolcanic rocks, mafic and ultramafic intrusive rocks and chemical metasedimentary rocks. A pair of adjacent shear zones (A and B) striking approximately ($40^{\circ}/220^{\circ}$) marks the boundary between the intermediate to mafic metavolcanics and the mafic and ultramafic intrusive rocks in the area. The southern shear zone is known to be spatially correlated and hosting the mineralization structure (gold-bearing quartz vein) on site as discussed in detail within (Watson 1929; Harris 1970 and Chorlton 1987).

The two shear zones have clear topographic expressions, appearing as lineaments in the UAV-borne DEM, shown in Figure 9(a). The DEM was derived from the processed UAV-borne laser altimeter data and was comparable to both the regional ~ 30 m DEM from the Canadian Digital Elevation Data (CDED) and the ~ 100 m heliborne DEM. The UAV-borne laser altimeter data was processed to remove non-ground returns (treetop canopy, branches and other foliage) and low-intensity returns over open bodies of water. The two shear zones (dashed purple lines) and their topographic depressions are visible in the DigitalGlobe WorldView-1 satellite imagery of the Moss Lake area taken in August 2016, as shown in Figure 9(b).

Through comparing the gathered 35 m flight elevation UAV-borne magnetic data with the geologic, topographic and optical data, it becomes clear that the two targeted trends of magnetic highs

correspond structurally to the pair of adjacent shear zones. Figure 10 demonstrates the spatial correlation between the positive magnetic anomalies, the mapped extent of the shear zones (purple dashed lines A and B), the topographic expressions of the shear zones and their visual extent. This is most noticeable in the northern shear zone where the positive magnetic anomaly is spatially correlated with its entire length. This is not the case for the southern shear zone, where the magnetic signature only extends to approximately (200 m E, 200 m N), while both the visual extent and topographic expression continue towards the Northeast. The direct spatial correlation between the shear zones and the magnetic anomalies were not previously understood from the airborne magnetic data alone and provided an enhanced structural interpretation of the area of interest.

A known secondary shear structure striking approximately $45^{\circ}/225^{\circ}$ (purple dashed line C, Figure 10) was resolved in the 35 m and 45 m UAV-borne aeromagnetic surveys, where the magnetic signature related to shear zone (B) curls towards the East and terminates. This relatively small and localized magnetic feature occurs along trend of the known secondary shear structure that hosts a gold mineralization occurrence. This known mineralization structure (C) was previously trenched and sampled by the property owners prior to the UAV-borne survey being conducted. The magnetic signature associated with this secondary shear zone (C) is only present where it intersects with the primary shear structure (B) and is not resolvable further north along the shear zone within the mafic metavolcanic rocks. This magnetic feature at the intersection of shear zones (B) and (C) was not observed in the aeromagnetic data collected at the 85 m or 70 m flight elevations, further demonstrating the resolution and sensitivity benefits of low flight elevation UAV-borne aeromagnetic data.

Unmanned Aerial Vehicle First Vertical Derivative Data

The first vertical derivative magnetic map, created by calculating the vertical gradient between the 35 m and 45 m flight elevation UAV-borne magnetic data, provides a further increase in resolution, as shown in Figure 11. This magnetic map was the only airborne product able to resolve the Northeastern structural trace of shear zone B, (dashed purple line). The magnetic signature associated to the known secondary shear structure (C), striking approximately ($45^{\circ}/225^{\circ}$), is outlined in greater detail

occurring at the intersection with shear zone (B). The increased resolution and sensitivity of the low flight elevation UAV-borne aeromagnetic survey also resolved and highlighted a previously undiscovered magnetic structural trend (D) between shear zones (A) and (B). The interpretation of this structure, directly from the UAV-borne first vertical derivative map, led to a new gold discovery assayed at 15.7 g/t along this previously unidentified mineralized shear zone.

Terrestrial Magnetic Data

A residual magnetic intensity plot of the Moss Lake area was produced from the terrestrial magnetic data and is shown in Figure 12. The terrestrial data outlines the location and extent of shear zones (A) and (B) with crosscuts of the structures throughout the study area. The terrestrial magnetic data was also able to verify the positive RMI structure observed at the intersection of shear zones (B) and (C), as well as the localized and discontinuous positive RMI structures along the newly discovered shear zone (D). These discontinuous positive RMI signatures located along shear zone (D) overlap and match the magnetic features sensed in the UAV-borne aeromagnetic first vertical derivative map. This is illustrated in Figure 13, where the terrestrial magnetic plot is overlain on the UAV-borne first vertical derivative map. The comparison of the terrestrial and UAV-borne first vertical derivative data provided in Figure 13, demonstrates a striking similarity in the resolvability, position and extent of these positive RMI signatures where the two datasets overlap. Overall, the terrestrial magnetic data was able to verify the shapes and extents of the positive RMI structures observed and interpreted in the UAV-borne aeromagnetic survey.

Upward Continuation of the Unmanned Aerial Vehicle Magnetic Data

Although the first vertical derivative was directly measured as part of this case study by flying a sequential series of UAV-borne aeromagnetic grids at multiple flight elevations, this is not a practical, nor efficient surveying practice for industrial applications. The reason is that upward continuation starting from the same 35 m UAV-borne flight elevation could have provided near identical vertical gradient results and residual magnetic intensity grids without having to fly the additional two survey heights. The exercise of flying near identical grids at multiple flight elevations over the same area

within this case study was conducted to empirically verify the process of upward continuation on a vertical scale of less than 100 m, while over variable and complex geological terrain. The 35 m flight elevation UAV-borne data were upward continued to 45 m, 70 m and 85 m AGL using a 2-dimensional, algorithm within the wave-number domain. Through comparing the upward continued data at the 45 m, 70 m and 85 m flight elevations, with the data that were physically collected by the UAV and manned helicopter from these flight elevations, it was found that each of the respective data sets were comparable. This is illustrated in Figure 14, where the upward continued residual magnetic intensity grids and the differences between the upward continued and directly measured magnetic fields are demonstrated for the 45 m and 70 m UAV-borne flight elevations. This empirically confirms that there is not a direct benefit of conducting multiple flight elevation UAV-borne aeromagnetic surveys for industrial applications and that upward continuation is a practical and valid method to calculate vertical gradients as has been standard practice throughout industry.

The differences that do occur between the upward continued data and the data physically measured at all three flight elevations was within the margin of error (± 2.5 m) associated to the accuracy of the UAV's GPS elevation measurements throughout all surveys. This results in a possible error up to $\sim \pm 25$ nT over the positive vertical magnetic gradient areas ($\sim +10$ nT/m) within the 35 m flight elevation dataset alone and is compounded when including the same margin of error (± 2.5 m) associated with the higher UAV-borne flight elevations. Further error exceeding this ± 25 nT threshold is present below the 100 m north line and attributed to a difference in flight lines between the 35 m flight elevation survey and the 45 m and 70 m over shear zone (B) and on the edges of the grids where there are predominately vertical high gradients.

DISCUSSION

Within this case study, the UAV-borne aeromagnetic data flown at a height of 35 m AGL provided a higher resolution data product when compared to the regional manned airborne magnetic data flown at 85 m AGL. Presently, the increased resolution of UAV-borne aeromagnetic surveys can be best applied to further assess previously identified areas of interest from manned airborne surveys on a

more localized scale of 1 – 10's km². This is most applicable when the ground cover, terrain and site conditions make terrestrial magnetic surveying logistically complex and expensive in both time and cost, as was demonstrated herein.

It is foreseeable that UAV-borne magnetometry will be widely implemented into the industrial marketplace to broaden the toolset available in mineral exploration. The application of UAV-borne aeromagnetic surveys will fall between the applications of manned airborne and terrestrial magnetic surveys, but with it likely overlapping more within the domain of terrestrial magnetic surveys. This is due to the relatively similar high-resolution data products and limited effective coverage area both UAV-borne and terrestrial magnetic surveys exhibit when compared to manned airborne magnetic surveys. The benefits of UAV-borne aeromagnetic surveying over terrestrial surveying include increased coverage rates (ex. two hours for the 35 m UAV-borne flight elevation vs 5 eight-hour days for the terrestrial survey) and the ability to provide a superior logistical advantage for various site conditions (ex. cutlines are not required and increased ease of circumnavigating cliffs and waterbodies). Future technological advancements of UAV platforms will undoubtedly be focused on increasing their coverage and flight endurance capabilities, potentially allowing them to effectively and economically survey areas up to 10's km² at an increased resolution and in a full tensor magnetometry mode. This advancement will increase the surveying efficiency providing a further advantage compared to terrestrial surveys but will not compete with the effective coverage rate (>30 m/s), flight endurance (10's of hours) and survey areas (100's km²) able to be flown by manned aeromagnetic surveys.

The first vertical derivative maps, calculated from the UAV-borne magnetic data collected at a height of 35 m and 45 m and derived through upward continuation of the 35 m flight elevation, provided the highest overall data resolution of the airborne surveys. This data product allowed for the detection and interpretation of a new mineralization target along the previously undiscovered shear zone (D). The follow-up terrestrial magnetic survey was able to validate the features sensed by the 35 m flight elevation survey and visualized within the first vertical derivative magnetic map. This case study exemplifies an application where low flight elevation UAV-borne aeromagnetic surveys

coupled with the derivation of the vertical gradient was able to meet the objectives set forth by the survey and provide meaningful results in the form of a new discovery. While the terrestrial magnetic survey also met these objectives by sensing the same magnetic structures at an even higher resolution, this benefit is overshadowed by the challenges associated to collecting the terrestrial data and the time/effort/cost required. This balance between data coverage, data resolution and logistical efficiency is the main technical advantage provided by UAV-borne aeromagnetic surveys, over terrestrial magnetic surveys.

After comparing the multiple data sets within this case study, it was clear that the two targeted positive RMI anomaly trends (A and B) occurred directly over a pair of adjacent shear zones, striking approximately $40^{\circ}/220^{\circ}$ (Osmani 1997). Typically, the occurrence of a shear zone is identified in aeromagnetic data due to the presence of an offset magnetic anomaly trend or due to sharp transitions in RMI values, where two geologic units of different magnetic susceptibility have been offset or emplaced next to one another. In this case however, the structure of the shear zones (A & B) are directly hosting or controlling a localized positive RMI anomaly along their strike length. This is not a typical material property of shear zones, as they do not significantly alter the magnetic susceptibility of the geologic units in which they are hosted. A ground magnetic report (Bayne 1984) noted the presence of these positive RMI anomalies along the same strike as the shear zones but did not identify the two shear zones as the source directly controlling the spatial distribution of the RMI anomalies. The two possible explanations put forth by Bayne (1984), included: a change in the composition of the mafic intrusive rocks or the possibility that a section of the banded iron formation had been enclaved within the intrusive rocks. Neither of these explanations are fully consistent with the gathered UAV-borne aeromagnetic data herein, that demonstrate the RMI anomalies being localized directly overtop both shear zones and variable in magnitude along their strike lengths.

An integrated hypothesis is that the observed and mapped shear zones preferentially developed within occurrences of relatively weaker ultramafic intrusive/metavolcanic rocks situated between the mafic intrusive and mafic metavolcanic rocks. The variable amplitude of the magnetic anomalies could have been caused by hydrothermal fluids flowing along the length of the shear zones

and interacting with the ultramafic rocks and the metavolcanic rocks. This would cause the ultramafic rocks to undergo varying degrees of alteration, such as serpentinization, a process which forms magnetite (Parvar et al. 2018) or iron-carbonatization, a process which forms the mineral(s) ankerite and/or ferrous dolomite (Osmani 1997). While the process of serpentinization would lead to distinctly resolvable positive RMI anomalies that match the large amplitudes (400 – 700 nT) measured over sections of these shear zones, the process of iron-carbonatization would only produce discrete positive RMI anomalies, as ankerite and ferrous dolomite have significantly lower magnetic susceptibilities than magnetite. Within the 35 m UAV-borne magnetic map, shear zone A and the southern section of shear zone B are likely hosted in thin layers of ultramafic rocks that have undergone serpentinization producing these relatively large positive RMI anomalies. While the Northern section of shear zone B is likely hosted with the mafic metavolcanics rocks that has been subjected to iron carbonatization and not serpentinization, leading to the discrete positive RMI magnetic signature observed in the UAV-borne first vertical derivative data and the terrestrial magnetic survey.

Evidence supporting this hypothesis was compiled by examining the historic geological reports of the area and integrating this information with the UAV-borne aeromagnetic survey. Ultramafic intrusive/metavolcanic rocks are present within and surrounding the Moss Lake area, but Osmani (1997) states that “in most outcrops the ultramafic units are only a minor component within the mafic intrusive/metavolcanic rocks and thus cannot be portrayed as an independent map unit. The contact relationship with the mafic intrusive/metavolcanic rocks is rarely observed. In most cases, contacts are obscured by shearing and/or by intense alteration (e.g., serpentinization and iron-carbonatization).” Chorlton (1987) also independently observed an abundance of iron carbonate minerals (ferrous dolomite) staining the northern section of shear zone (B) within the mafic metavolcanic units of the study area. Typically, ultramafic rocks also preferentially eroded compared to other more resistant rock types creating topographic depressions that can become filled with water bodies (ie. swamps/wetlands). Topographic depressions filled with wetlands were observed during the terrestrial magnetic survey and correlated with the positive RMI values measured directly overtop of the mapped shear zones (A) and (B). Due to the presence of these wetlands and the meter of snow on

the ground during the field visit, outcrop samples were not able to be collected over shear zones (A) and (B) to verify this hypothesis.

CONCLUSIONS

Within this case study, the UAV-borne aeromagnetic survey conducted at the 35 m flight elevation provided a practical balance between the existing coverage and resolution capabilities of both the airborne and terrestrial magnetic surveys on a scale of $\sim 1 \text{ km}^2$. The calculated UAV-borne first vertical derivative map from the 35 m flight elevation data provided the highest overall resolution of the airborne products and outlined structural trends not previously identified within the study area. A follow-up field campaign, guided by the results of the UAV-borne aeromagnetic survey, yielded a new gold discovery assayed at 15.7 g/t hosted in the north-eastern extension of the newly discovered shear zone (D). Based on comparing the operational logistics, time investment, data coverage and data resolution of the UAV-borne aeromagnetic survey verses the terrestrial survey, it was concluded that the UAV-borne aeromagnetic survey provided the better overall efficiency, experience and data product in this application and field setting.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA SHARING

The aeromagnetic data that support the findings of this study are available in GeologyOntario at [<http://www.geologyontario.mndm.gov.on.ca/index.html>], reference number: OGS GDS 1241.

The UAV-borne and terrestrial data are available from the authors with the permission of Kesselrun Resources Inc.

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Figure 1 Diagram showing the coverage and resolution capabilities of manned airborne and terrestrial magnetic surveys compared to the capabilities of UAV-borne aeromagnetic surveys. The yellow line represents the possible coverage and resolution ranges of UAV-borne aeromagnetic surveys, depending primarily on the flight elevation (resolution) and flight speed (coverage).

Figure 2 A 4 km x 4 km regional geologic map of the Moss Lake area modified after (Osmani 1997). The 500 m x 700 m survey area where the UAV-borne aeromagnetic survey occurred is outlined by the purple rectangle. The coordinates (0 ,0) correspond to UTM zone 15 U, coordinates of (663000 m E, 5377000 m N).

Figure 3 The 4 km x 4 km gridded regional heliborne aeromagnetic survey modified after Ontario Geological Survey, Geophysical Data Set 1241. The 500 m x 700 m survey area of the UAV-borne aeromagnetic survey is outlined by the purple rectangle. The coordinates (0 ,0) correspond to UTM zone 15 U, coordinates of (663000 m E, 5377000 m N).

Figure 4 UAV-borne platform, data acquisition system and semi-rigidly mounted potassium vapour magnetometer during a test flight on February 22, 2017

Figure 5 Diagram showing the elevation above the ground where each of the manned airborne (85 m), UAV-borne (70 m, 45 m, & 35 m) and terrestrial (2 m) magnetic surveys were conducted.

Figure 6 Profile of the UAV-borne total magnetic field data at a flight elevation of 35 m, demonstrating the TMI obtained along two adjacent 700 m long survey lines (blue) and throughout two corners (red). The calculated fourth difference of the magnetic data is plotted below with the green rectangle highlighting the industry standard of ± 0.05 nT for aeromagnetic surveys (Coyle et al., 2014).

Figure 7 (a) RMI map produced from the regional heliborne survey conducted at an 85 m flight elevation AGL and a 100 m line spacing. (b) UAV-borne RMI map produced from a flight elevation of 70 m AGL, (c) 45 m AGL, and (d) 35 m AGL, all using an approximate line spacing of 25 m. The crosslines at the 35 m flight elevation were flown with a line spacing of approximately 60 m. The flight lines of each survey are plotted using dots with a red center and black outline.

Figure 8 Local geological map of the Moss Lake area modified after (Osmani 1997), showing a pair of shear zones (A & B), separated by approximately 200 m, striking $40^{\circ}/220^{\circ}$ through the study area.

Figure 9 (a) The UAV-borne DEM of the Moss Lake area showing the topographic depressions of the two shear zones. The topography of the area varied from approximately 435 m to 475 m ASL. (b) Satellite imagery of the UAV-borne survey area with the interpreted shear zone outlines (A & B, purple dashed lines) georeferenced from (Osmani 1997).

Figure 10 The 35 m flight elevation UAV-borne aeromagnetic map and the georeferenced extent of the two mapped shear zones (A & B, purple dashed lines), demonstrating the spatial correlation between the magnetic field readings and the extent of the shear zones. Note: The southern shear zone (B) does not have a resolvable total magnetic field signature associated with the north-eastern extent, above (200 m E, 200 m N).

Figure 11 The first vertical derivative map calculated from the 35 m and 45 m UAV-borne magnetic data (valid at 40 m flight elevation), compiled with the mapped and interpreted extent of shear zones (A, B, C, and D, purple dashed lines). Note: The southern shear zone (B) has a resolvable signature associated with the north-eastern extent and a previously unknown shear zone and mineralization structure (D) was interpreted between shear zones (A & B).

Figure 12 The terrestrial magnetic dataset conducted over 5 days in April 2019.

Figure 13 The first vertical derivative map calculated from the 35 m and 45 m UAV-borne magnetic data compiled with the follow-up terrestrial magnetic survey. Note: The terrestrial magnetic survey verifies the location of the magnetic features observed along each of the interpreted shear zones (A, B, C & D) from the UAV-borne first vertical derivative map. The colorbar for the first vertical derivative data is in the top-right while the colorbar for the terrestrial magnetic data is in the bottom-right of the figure.

Figure 14 The 35 m flight elevation residual magnetic intensity grid upward continued to (a) 45 m AGL, and (b) 70 m AGL. The difference between the upward continued residual magnetic intensity grid subtracted from the directly measured residual magnetic intensity grid at (c) 45 m flight elevation, and (d) 70 m flight elevation.

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