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Front cover:
DJI Matrice 600 Pro aircraft mounted with a GSMP-35U magnetometer (DRONEmag) flying from right to left at a height of about 7.5 m above ground level. **Photo by Katya Zaborniak.**

Back cover:
Pilot performing a manual landing of a DJI Matrice 600 Pro aircraft mounted with a GSMP-35U magnetometer (DRONEmag) **Photo by Katya Zaborniak.**

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Abstract

Remotely piloted aircraft systems (RPAS) enable rapid collection of airborne magnetic data using miniaturized magnetometer payloads. We flew two RPAS magnetometer surveys over part of the Deerhorn alkalic porphyry Cu-Au occurrence in British Columbia's Interior Plateau: a large low-resolution survey at 97.5 m above ground level with 100 m traverse line spacing and a smaller high-resolution survey at 10 m above ground level with 5 m traverse line spacing. Collection of precise, high spatial resolution magnetic data was made possible by terrain following surveys, with altitude above ground maintained by an active RPAS-mounted radar altimeter or by three-dimensional waypoints from a 25 m digital elevation model. We produced two data-rich and two data-poor models of three-dimensional magnetic susceptibility in surface sediments from our RPAS surveys and supplemented by an existing helicopter-acquired magnetic dataset, surficial geology mapping, magnetic depth to source analysis, and depth to bedrock values from exploration drill-hole data. The high-resolution and low-resolution surveys produced inverted models with cell volumes of 0.98 m^3 and 612.5 m^3. Magnetite contents in the Deerhorn study area and the RPAS survey designs we used did not allow separating the near-surface sediment response from the underlying bedrock. Areally larger, high-resolution RPAS surveys over sediments with higher magnetic susceptibility may better isolate the surface component and be used to supplement traditional till geochemical or mineralogical surveys.

Keywords: remotely piloted aircraft system, drone, magnetometer, GEM Systems DRONEmag, magnetic inversion, subglacial till, surficial geology, Interior Plateau, drift prospecting

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1. Introduction

Airborne magnetic data are commonly used to measure the spatial distribution and abundance of magnetic minerals in subsurface bedrock. These signatures commonly correspond to the measured material's magnetite content, a primary and hydrothermal mineral in porphyry systems. In alkalic and calc-alkaline porphyry Cu±Mo±Au deposits, hydrothermal alteration can create secondary or destroy primary magnetite, leading to a modified magnetic intensity at porphyry centres (Byrne et al., 2019). Magnetite can be preserved in glacial sediments derived from porphyry occurrences and may form a dispersal train that can theoretically be used to locate buried up-ice occurrences (Pisiak et al., 2014, 2017; Plouffe et al., 2017). Unlike traditional till samples, magnetometers can remotely sense magnetic anomalies reflecting the abundance of magnetite beneath the immediate surface (>2 m), enabling bedrock geology, and possibly magnetite-bearing sediments, to be mapped in three-dimensions (Telford et al., 1990; Hansen et al., 2005).

Remotely piloted aircraft systems (RPAS) can collect magnetic data to guide field projects at relatively low cost and in near-real time (Elia et al., 2023). RPAS surveys enable data collection at very high densities (up to 5 m traverse line spacing) and closer to the ground than most helicopter or fixed-wing surveys. These advantages enable detecting magnetic anomalies from smaller, shallow sources (Hansen et al., 2005). Compared to ground-based magnetic methods, RPAS data are spatially more uniform (equidistant line and point spacing), collected faster, and can be acquired over environmentally sensitive or hard-to-navigate ground (Walter et al., 2020; Stele et al., 2022).

In 2019, the British Columbia Geological Survey (BCGS) started a program to assess applying remotely piloted aircraft systems (RPAS) to surficial geology mapping and drift prospecting. The project began with a small, consumer quadcopter RPAS with a fixed RGB camera to assist with surficial geology mapping in north-central British Columbia (Elia and Ferbey, 2020) and evolved to using a larger RPAS hexacopter with external geophysical payloads to evaluate the ability of RPAS-borne sensors to map and characterize the composition of surficial sediments in the Interior Plateau (Fig. 1; Elia et al., 2023, 2024). From 2021 to 2022, 53 autopilot air photo, lidar, magnetics, and radiometrics surveys were flown at 13 sites over subglacial tills derived from contrasting rock types. Elia et al. (2023) presented the complete geophysics and geomatics datasets collected and, for each sensor, how the data were acquired and processed. In this report we evaluate the use of RPAS-acquired data to separate the magnetic components of bedrock and surface sediments from one of our study areas, over part of the Deerhorn alkalic porphyry Cu-Au porphyry occurrence at the Woodjam developed prospect, 8 km southeast of the community of Horsefly (Fig. 1).

2. Setting

We conducted RPAS surveys in the Interior Plateau, an area of central British Columbia with extensive glacial sediments and isolated bedrock outcrop (Holland, 1976). It is underlain by rocks of Stikine and Quesnel terranes that host porphyry mines and numerous mineral occurrences (e.g., Nelson et al., 2013). Surveys were completed in the Mount Polley mine (alkalic Au-Cu porphyry), Woodjam developed prospect (alkalic to calc-alkaline Cu-Au-Mo porphyry; including the Deerhorn site, 22TFE0002 of the present study), and Guichon Creek batholith (Highland Valley calc-alkaline Cu-Mo porphyry mine) areas (Fig. 1). These areas are underlain by subglacial till, identified using existing surficial geology mapping (Bichler and Bobrowsky, 2003; Hashmi et al., 2015; Ferbey et al., 2016; Plouffe and Ferbey, 2018), and confirmed in the field in road cuts and soil pits.

2.1. Bedrock geology

The Woodjam developed prospect is on the northern margin of the Takomkane batholith (Early Jurassic), a calc-alkaline body that intrudes Nicola Group (Early Jurassic) volcanic and volcanosedimentary rocks (Sherlock et al., 2013; Laird, 2017). The Deerhorn alkalic porphyry Cu-Au mineralized zone is northwest of the batholith, in related monzonitic satellite intrusions and Nicola Group sandstones and brecciated to massive andesites (Fig. 2; Logan et al., 2010; del Real et al., 2014). At Deerhorn, potassium feldspar-biotite-magnetite alteration is common in monzonite intrusions and surrounding volcanic rock. The main mineralized zones are in this assemblage (del Real et al., 2013). Ore minerals include chalcopyrite, bornite, and molybdenite. Younger Chilcotin Group (Miocene) olivine-phyric basalts and Kamloops Group (Eocene) volcanic and sedimentary rocks unconformably overlie these older prospective rocks. Ground magnetic data have been used at Woodjam to locate drill targets, and borehole magnetic data have been used to log drill holes. In regional airborne magnetic data, Deerhorn shows as a magnetic high (Sherlock et al., 2012, 2013; Shives et al., 2004).

2.2. Quaternary geology

The Deerhorn area is underlain by subglacial till mapped mostly as a till blanket (>2 m thick) but smaller areas of thinner till veneer (<2 m thick) occur locally (Fig. 3; Ferbey et al., 2016). Glaciofluvial sands and gravels and lacustrine silts are in the northern and southern parts of the survey area (Fig. 3). A diamond drill hole in the survey area, completed as part of property-scale exploration, indicates surface sediments there are ~29 m thick (Fig. 3; DH10-10). It is unlikely that this sediment package is entirely composed of subglacial till but the drill hole log does not differentiate between sediment types. Tills observed at the surface above the drill hole are moderately consolidated and contain pebble-sized clasts.

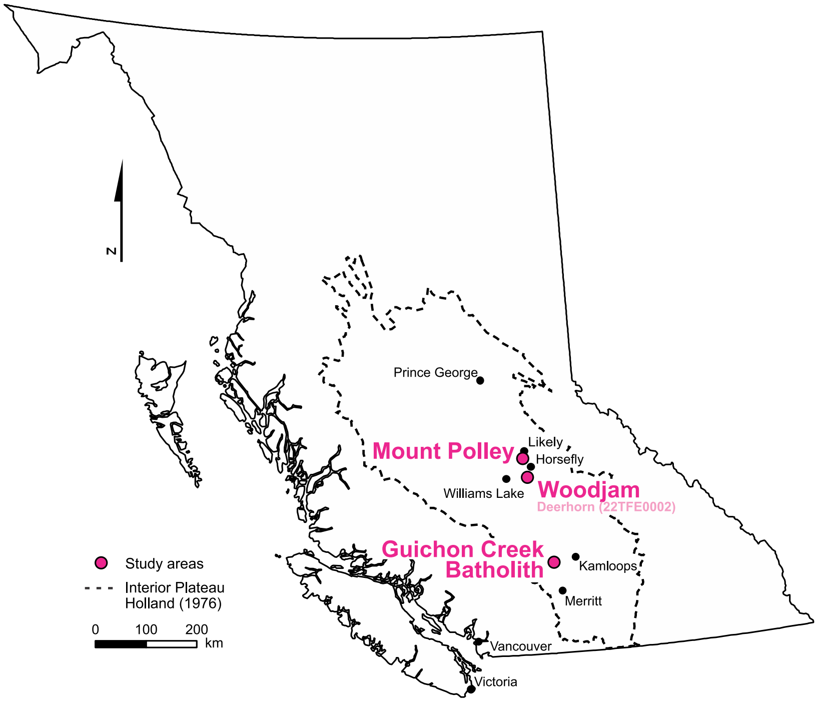

Fig. 1. Location of Deerhorn (22TFE0002) RPAS survey and other BCGS RPAS surveys.

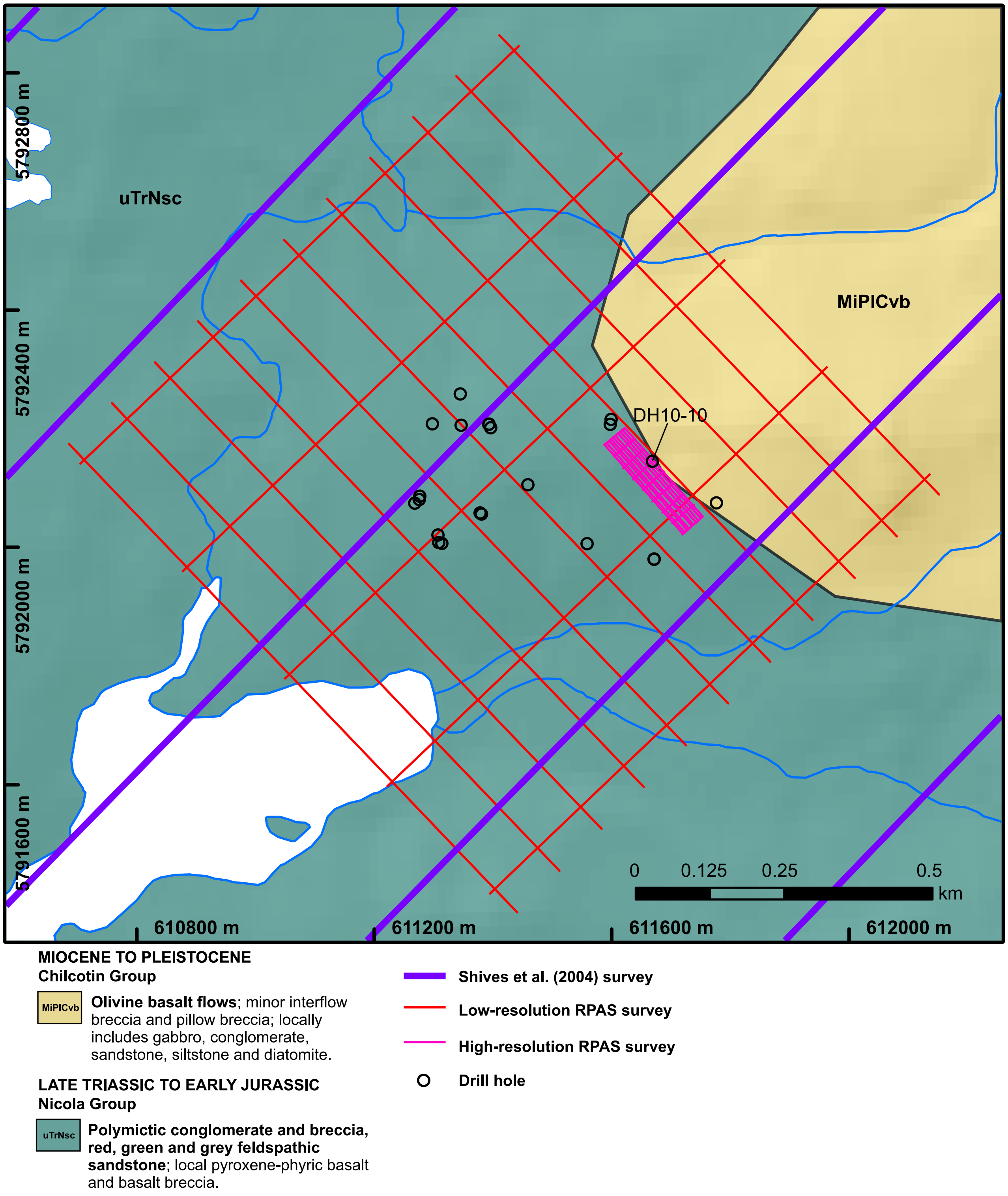

Fig. 2. Bedrock geology of the Deerhorn (22TFE0002) RPAS survey area (modified from Logan et al., 2010) with airborne magnetic survey lines.

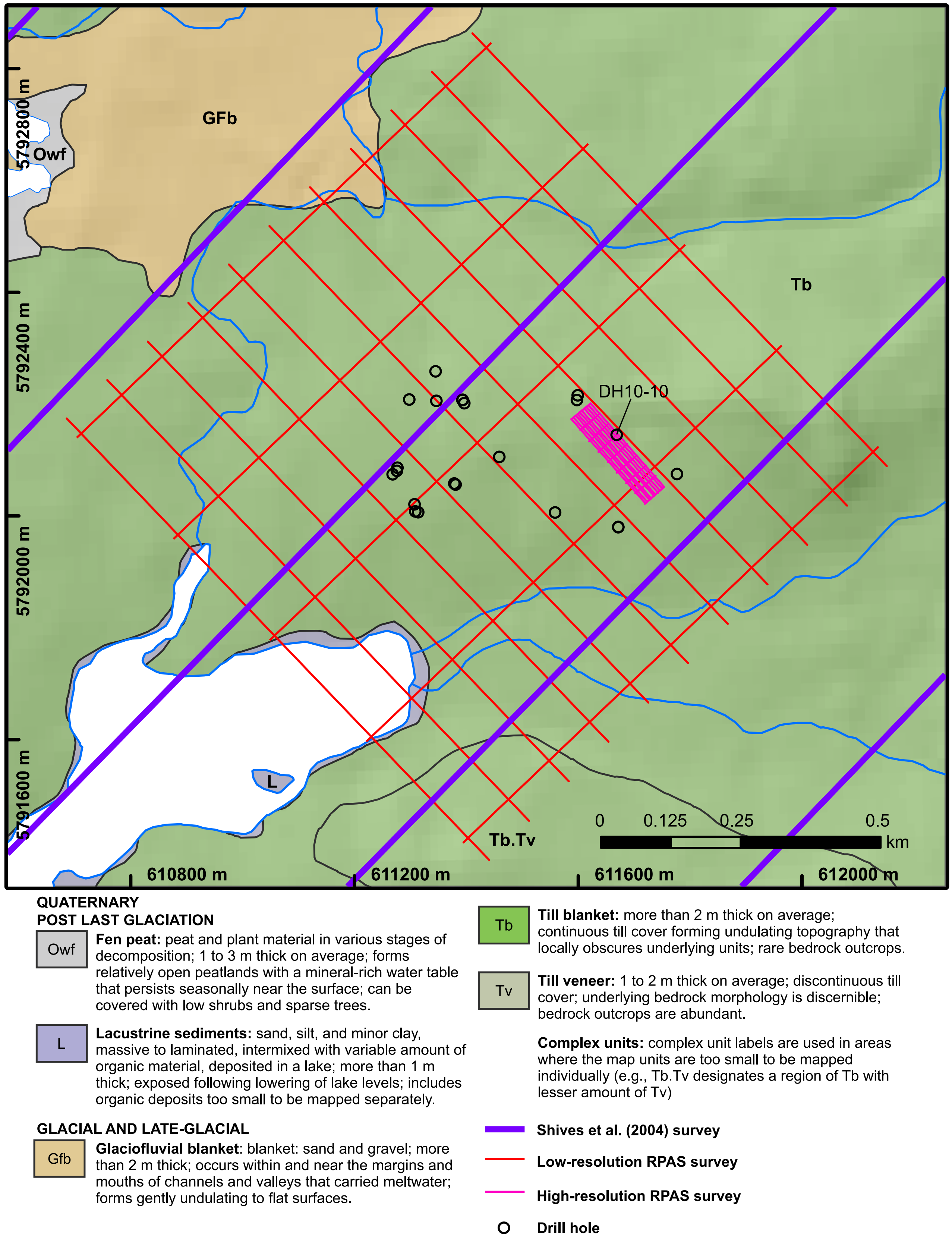

Fig. 3. Surficial geology of the Deerhorn (22TFE0002) RPAS survey area (modified from Ferbey et al., 2016) with airborne magnetics survey lines.

3. Methods

3.1. RPAS aircraft

All surveys were flown in recent forestry cutblocks so that the RPAS and payload remained within visual line of sight and could safely conduct terrain-following surveys at 5-10 m above ground level. A DJI Matrice 600 Pro (M600) was used to acquire magnetic data (Fig. 4). It was modified with an SPH Engineering radar altimeter and SkyHub which integrates with the DJI flight control systems and Universal Ground Control Software (UgCS), the flight planning package used to design and fly autopilot surveys. Maintaining a constant altitude above ground ensures that measured data variation is related to geology, not changes in distance between the source and detector. To this end, UgCS's true terrain following mode and data collected by the radar altimeter were used to fly surveys in cutblocks, between 5 and 10 m above ground level (±50 cm, depending on vegetation cover). Surveys designed in UgCS to be flown over cutblocks and tree stands used a 25 m Canadian Digital Elevation Data digital elevation model (DEM) to maintain a constant altitude above ground.

3.2. RPAS magnetometer

We used a GSMP-35U (DRONEmag) magnetometer from GEM Systems (Fig. 4a). This sensor is built around an optically pumped potassium vapour magnetometer, with a sensitivity of 0.0002 nT and a sample rate of up to 20 Hz (GEM Systems, 2023a). The sensor was slung 2.5 m below the M600, with individual instrument components (battery, data logger) placed in a custom-made housing that attached to the mounting rails of the M600. The DRONEmag uses a dedicated GNSS antenna (mounted to the top of the aircraft) to collect the x and y positions and a laser altimeter (mounted to the front of the custom-made housing) to measure height above ground for each magnetic measurement. A GSM-19 Overhauser base station (Fig. 4b) collected magnetic readings at 5 Hz during RPAS surveys (GEM Systems, 2023b). GEM System's GEMLink software was used to initialize and set up the DRONEmag before flying a survey and perform a diurnal correction on the RPAS data following collection.

3.3. Survey design

We conducted two RPAS magnetics surveys over the Deerhorn survey area (22TFE0002). The first survey (high-resolution) was collected over a cutblock at 10 m above ground level with a line spacing of 5 m (Table 1). The survey consisted of 10 traverse lines and 9 tie lines that extended across a 200 x 50 m area. These data were collected at 2 m/s and 10 Hz, resulting in a measurement every 0.2 m. The second survey (low-resolution) was flown at 97.5 m above ground level and 100 m line spacing, above the first survey and extending over adjacent tree stands (Table 1). This survey consisted of 11 traverse lines and 5 tie lines across a 1000 x 800 m area. These data were collected at 10 m/s, resulting in a measurement every 1 m. The areal extent of this low-resolution survey was limited by Transport Canada's visual line-of-sight regulations, which state that the aircraft must always be in view.

We used ArcMap to remove points where the magnetometer did not collect data and to separate traverse and tie lines. Oasis Montaj was used to de-spike and level the magnetic data (traverse and tie lines) and create two-dimensional representations of the total field magnetic response using the bidirectional gridding function (resolution of one-third line spacing; Elia et al., 2023).

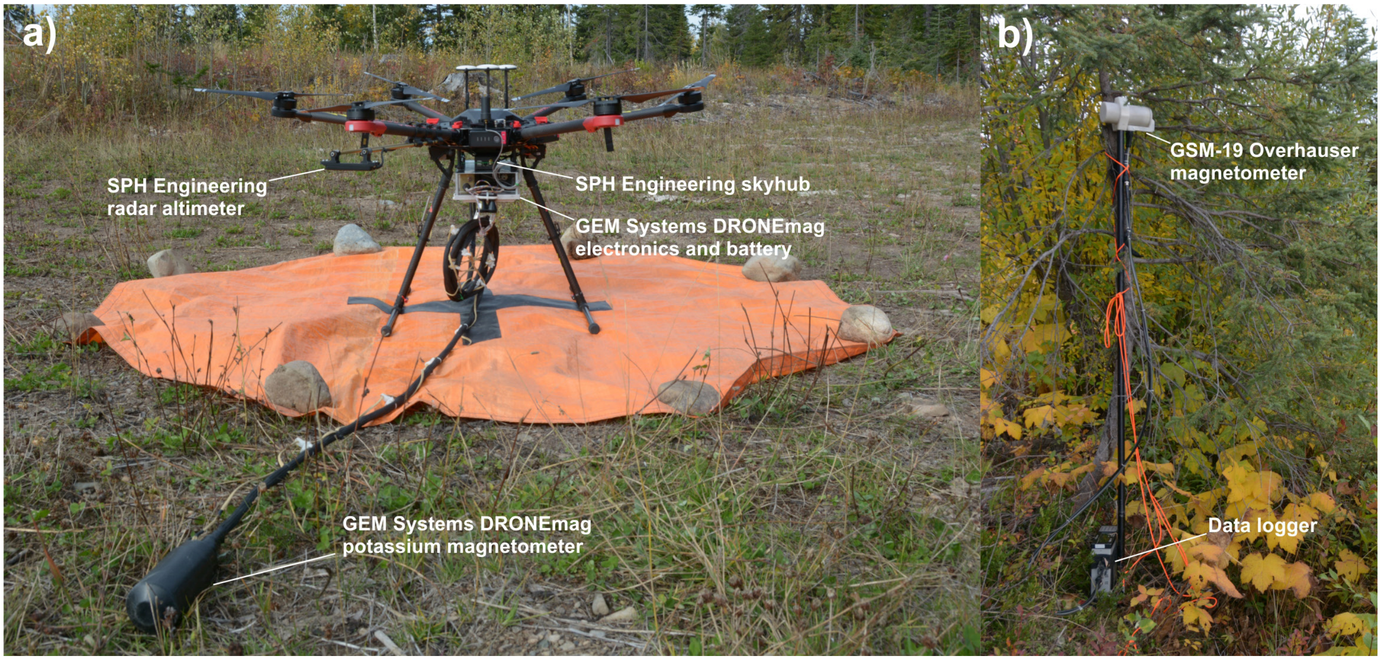

Fig. 4. RPAS magnetometer acquisition equipment. **a)** GEM Systems GSMP-35 U (DRONEmag) potassium magnetometer mounted on a DJI Matrice 600 Pro. The instrument's electronics and battery are housed in a custom tray mount. The magnetometer sensor is slung 2.5 m from the mount's base. **b)** GSM-19 Overhauser magnetometer attached to a tree; data logger at base.

Table 1. Aeromagnetic survey specifications.

Survey	Line spacing	Line azimuth	Sensor height	Platform
Shives et al. (2004)	500 m	90° N	110 m	Helicopter
Low resolution	100 m	136° N	98.5 m	RPAS
High resolution	5 m	138° N	10 m	RPAS

3.4. Regional-scale supplementary magnetic data

Geological Survey of Canada (GSC) regional-scale magnetic data by Shives et al. (2004) were used to supplement the RPAS data for geophysical inversions. These data were acquired using a cesium vapour magnetometer slung beneath a helicopter, sampling at 10 Hz with a sensitivity of 0.01 nT. These data were collected at 110 m above ground level along traverse lines spaced at 500 m and tie lines spaced at 4.0 km, to produce a gridded total field magnetic raster at 80 m spatial resolution. The ungridded data have a measurement every ~4 m.

3.5. Modelling

Our modelling approach used the acquired RPAS magnetics datasets to produce two data-rich and two data-poor models for defining depth to bedrock to better separate bedrock and cover magnetic responses. The model design considers high-frequency signals to be associated with near-surface sources and low-frequency signals with deeper bedrock sources. Differences in survey height and resolution also help separate sources in sediment from bedrock, because surveys closer to ground and with tighter line spacing capture signatures from discrete shallow features. The modelling used a series of software consisting of: GOCAD Mining Suite for geological and geophysical modelling; Geoscience ANALYST for compilation and visualization; and VPmg for inversion modelling.

The data-poor models were produced using surficial geology maps as a known input of till thickness (Ferbey et al., 2016; at outcrop till thickness = 0 m), and magnetic depth to source analysis (Euler deconvolution) to assess the depth to the top of magnetic features at the bedrock-cover contact. The data-rich models used known sediment thicknesses from exploration drill holes to re-fit the data-poor model and refine the sediment-bedrock contact. We consider that the data-rich model is a robust approach for assessing the performance of the method and validating the data-poor model.

Surface topography of the survey area was defined using an RPAS-acquired lidar DEM (Elia et al., 2023) combined with a bare-Earth canopy-adjusted regional radar DEM (25 m spatial resolution). The regional DEM required canopy adjustment of ~19 m, estimated from vegetation resource information data (Forest Analysis and Inventory Branch, 2023), to match with elevations in the lidar DEM.

For each till thickness input (data-rich and data-poor), a magnetic susceptibility model was produced from the gridded low-resolution (25 m x 25 m x 12.5 m minimum cell size; 612.5 m^3 cell volume), and high-resolution (1.25 m x 1.25 m x 0.625 m minimum cell size; 0.98 m^3 cell volume) RPAS datasets. To produce these models, magnetic data were initially inverted below the bedrock-cover contact to produce a two-dimensional horizontal physical property distribution below a homogeneous non-magnetic cover. The residual magnetic signal, assumed to be from magnetic sources in the sedimentary cover, was then assessed as the difference between the forward modelled bedrock magnetic response and the corresponding resolution RPAS magnetic data. The inverted bedrock magnetic susceptibility distribution was subsequently left fixed, and a three-dimensional physical property distribution was introduced in the cover unit to fit the remaining residual magnetic signal from the RPAS data. To produce the low-resolution model, data from Shives et al. (2004) were used to define the regional magnetic trends from material surrounding the model and for the bedrock inversion. The low-resolution RPAS data were used to estimate till thickness and for the sediment inversion. The high-resolution model used the low-resolution RPAS model to define the magnetic trends from surrounding material, estimate till thickness, and set the two-dimensional magnetic susceptibility distribution in bedrock and the high-resolution RPAS data for the sediment inversion.

4. Results

4.1. Total field

To illustrate the differences between RPAS and helicopter-borne datasets, we present gridded total field results of the low-resolution RPAS survey (33 m cell), the high-resolution RPAS survey (1.67 m cell), and 80 m cell magnetic data from Shives et al. (2004). The absolute values in Shives et al. (2004; 57,159-57,542 nT) are approximately 1,000 nT higher than the RPAS results due to being collected 18 years later in a different geomagnetic field. The absolute values of the low-resolution RPAS (55,916-56,434 nT) data are 15-30 nT lower than the high-resolution RPAS results (55,929-56,462 nT).

The contrast and range of magnetic total field values in the Shives et al. (2004) and low-resolution RPAS magnetics are similar (Fig. 5; 400-500 nT). Both contain a northwest-southeast magnetic high in the south and a magnetic low in the northwest. The contrast and range of magnetic total field values across the low-resolution and high-resolution RPAS magnetics are similar (500-550 nT). The high-resolution data shows more contrast compared to the same area within the low-resolution dataset. Both show the highest magnetic values in the southern portions of the high-resolution study area and the lowest in the north. The high-resolution magnetic data has an isolated circular magnetic high (10 m diameter) in the north-central study area that does not appear in the low-resolution data.

Differences in the magnetic values between each survey are likely explained by the data density differences between each model. This highlights the inherent properties of magnetic data in which intensity decreases and magnetic anomalies become smoother and of smaller amplitude as the height of the airborne magnetometer survey increases. RPAS data are typically collected at slower speeds and with tighter line spacings than standard helicopter surveys, which results in higher spatial resolutions and more robust gridded cell values that require less interpolation between lines.

4.2. Till thickness models

With drill hole data, the data-rich model provides a better estimate of sediment thickness than the data-poor model (Fig. 6). Differences in depth to bedrock (±20 m) are common in the central part of the area with a high density of exploration drill holes. The southwestern part of the model contains magnetic sources estimated from the depth to source analysis that

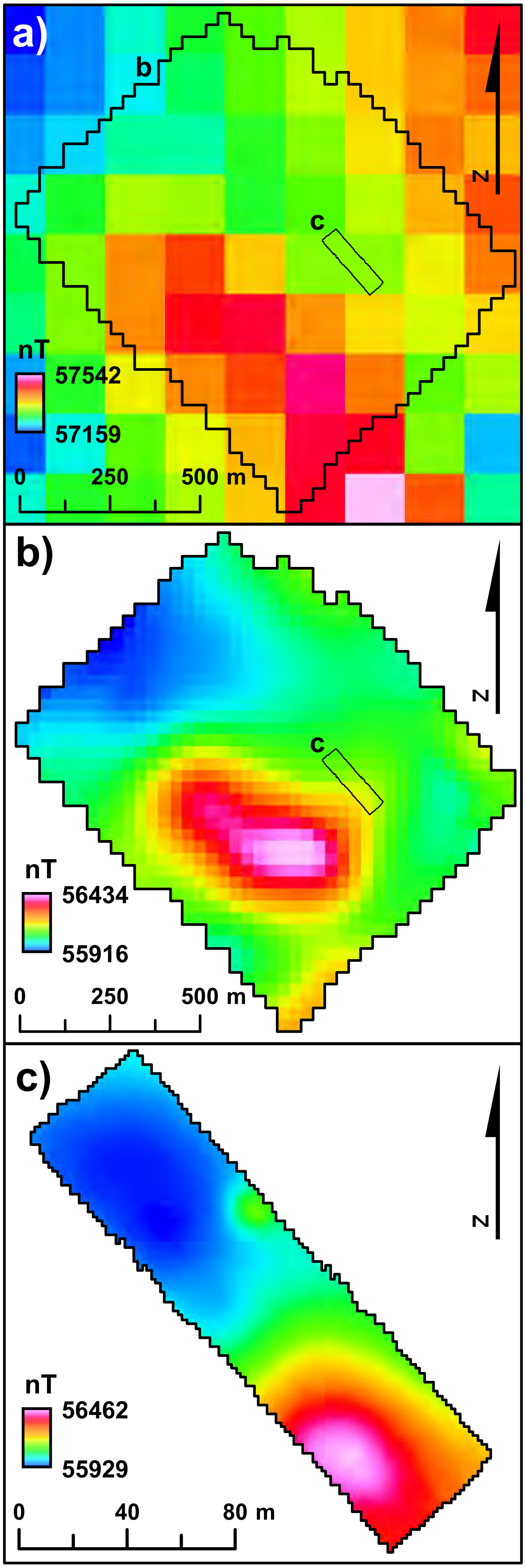

Fig. 5. Comparison of gridded magnetic total field data in the Deerhorn study area. The colour ramps correspond to the maximum and minimum total field values in each survey. **a)** Shives et al. (2004) survey with RPAS survey outlines. **b)** Low-resolution RPAS survey with the high-resolution survey outline (c). **c)** High-resolution RPAS survey.

provide better constraints on surface sediment thickness. There is a better agreement between drill-hole data and the data-poor model in the areas between these sources. Areas lacking magnetic source or drill hole data, such as the northern part of the survey, have similar depths to bedrock for data-rich and data-poor models.

4.3. Sediment susceptibility models

Data-rich and poor models show similar spatial distribution, size, and magnitude of magnetic anomalies in the sediment (Figs. 7, 8). The largest magnetic susceptibility highs in the sediment layer of the low-resolution models are directly above the magnetic highs identified in the bedrock models (Fig. 7), which suggests poor separation of signatures between rock and sediment. Data-rich and data-poor models exhibit magnetic susceptibility features in sediment (up to 0.01 SI) that do not correlate with underlying bedrock susceptibilities (Fig. 8). Although these features may suggest elevated magnetite concentrations in sediments, they cannot be confirmed without detailed sampling and quantifying magnetite concentrations.

The sediment layer of both high-resolution models has higher magnetic concentrations to the southeast (Fig. 8) with the data-rich model (Fig. 8b) appearing less concentrated and coherent relative to the data-poor model (Fig. 8a). A focused anomalous magnetic high in sediment aligns with the location of an exploration drill hole (DH10-10), which is better characterized by the high-resolution survey (Fig. 9). This high is visible in the sediment layer of both data-rich and data-poor models and is from metallic drill casing left in the drill hole.

5. Discussion

RPAS magnetic surveys benefit from their ability to fly closer to the ground to detect smaller magnetic variations from shallow sources. Control of sensor position and location becomes increasingly important as the distance between the magnetometer and the ground decreases to ensure consistent capture of magnetic source size and depth. Inaccuracies at low flight heights can be caused by the physical positioning of the aircraft during data acquisition, but also by errors related to the recorded GPS position by the magnetometer.

RPASs can rapidly fly surveys with tight line spacing (<100 m) to produce dense, high-quality point and gridded data; a critical advantage over traditional airborne surveys for geophysical inversion. Traditional geophysical surveys of similar line spacing are typically designed with two separate offset surveys with double the nominal line spacing for practical survey optimization purposes. For example, 100 m line-spaced datasets can consist of two 200 m line-spaced surveys that are horizontally offset by 100 m and combined to build a final product. Neighbouring lines in a final dataset may be flown on different days resulting in more complex post-processing as flight conditions, diurnal magnetic variations, and ground clearance from line to line can vary and lead to lower-quality geophysical inversions.

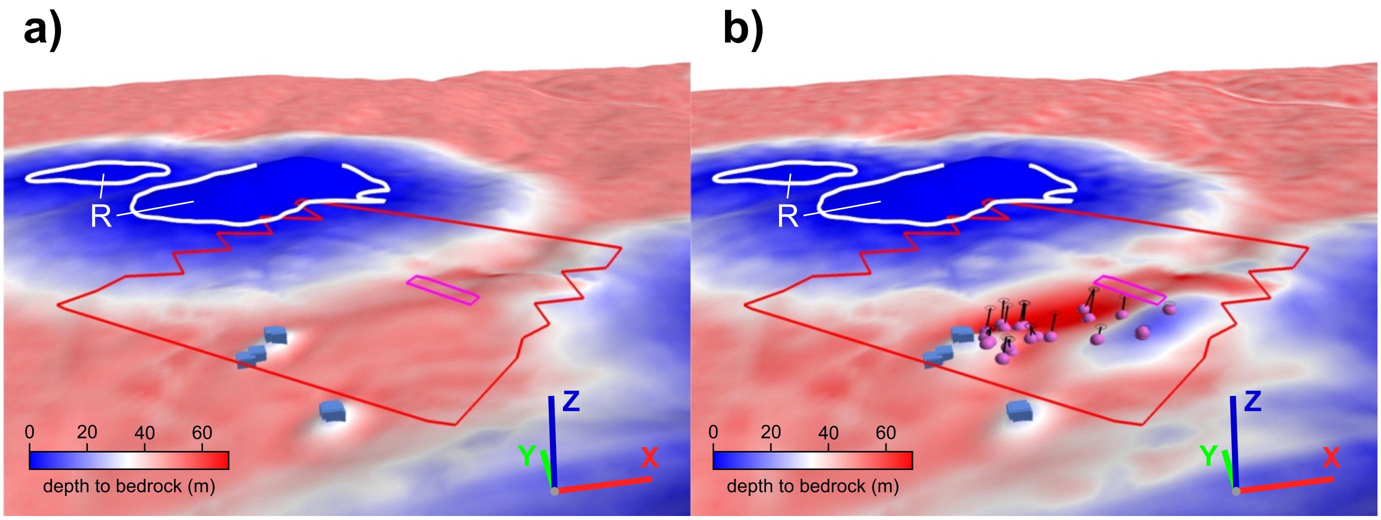

Fig. 6. 3D depth to bedrock models. **a)** Data-poor model. **b)** Data-rich model. Outlined in red is low-resolution RPAS survey; outlined in magenta is high-resolution RPAS survey. Blue cubes are magnetic sources, magenta spheres are drill hole-defined sediment-bedrock contacts, black lines are drill hole paths, white lines are bedrock outcrops.

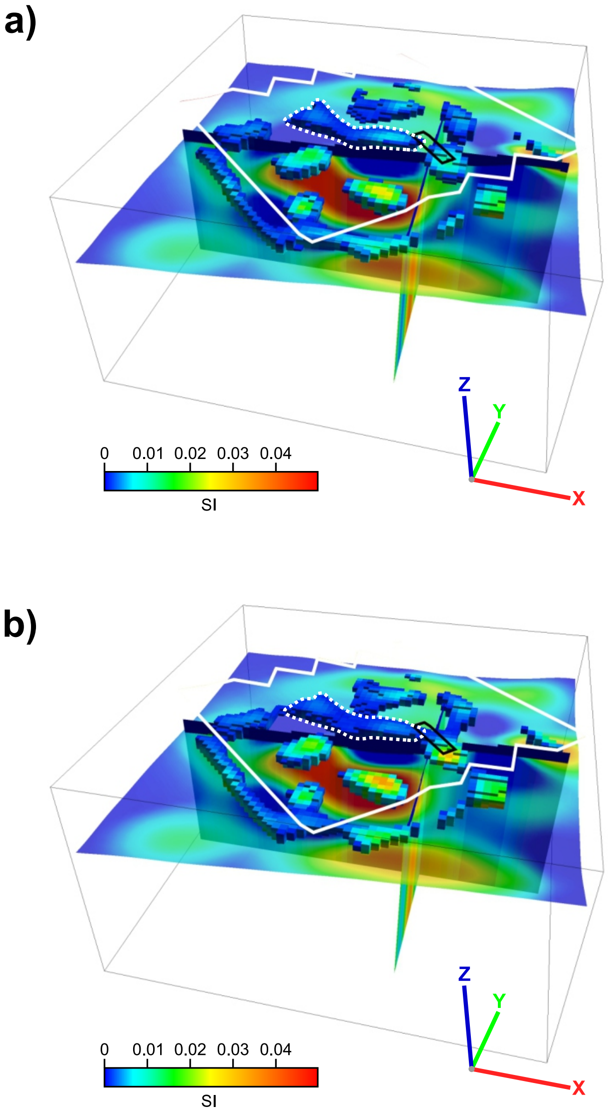

Fig. 7. Inverted low-resolution magnetic susceptibility model (SI). **a)** Data-poor model. **b)** Data-rich model. Outlined in white is low-resolution RPAS survey; outlined in black is high-resolution RPAS survey. White dotted line indicates a magnetic susceptibility high in sediment over a bedrock low. Top-of-bedrock surface coloured by bedrock magnetic susceptibility; cover with values > 0.0015 SI shown as blocks.

The magnetic depth to source analysis relies on the presence of resolvable magnetic anomalies. The amount and spatial distribution of these anomalies depend on the resolution and areal coverage of magnetic data and the magnetic susceptibility of bedrock in the survey area. The present study suggests that larger surveys, such as our low-resolution survey, are better suited to detect more magnetic anomalies in bedrock allowing better-defined depth to bedrock and isolation of the sediment's magnetic component. In this context, a larger areal coverage is more important than acquiring data as close to the ground as possible. Areas with minimal vegetation, such as at high altitudes or latitudes would result in a more accurate terrain following survey using the UgCS radar altimeter, and more accurate height above ground measurements by the DRONEmag laser altimeter. Less vegetation would also enable low flight heights (<30 m) and areally larger surveys while maintaining visual line of sight, maximizing the potential to measure magnetic anomalies. Our results show that in the Interior Plateau, RPAS surveys can be designed and flown at intermediate heights above ground (30-60 m) for larger areal coverage (i.e., flying above tree stands and not restricted to cutblocks) while providing the increased resolution required to map small near-surface magnetic features.

The data-rich model does not significantly improve on the data-poor model in its ability to detect smaller anomalies or redefine the bounds of existing ones. Because the magnetic features are not captured in their entirety along the model boundaries, the ability to measure the depth to bedrock and place anomalies in the rock layer is limited. The models do not contain any identifiable anomalies attributable to features in the sediment layer or patterns characteristic of mineral dispersal. Magnetite content in sediment may be too homogenous, or too

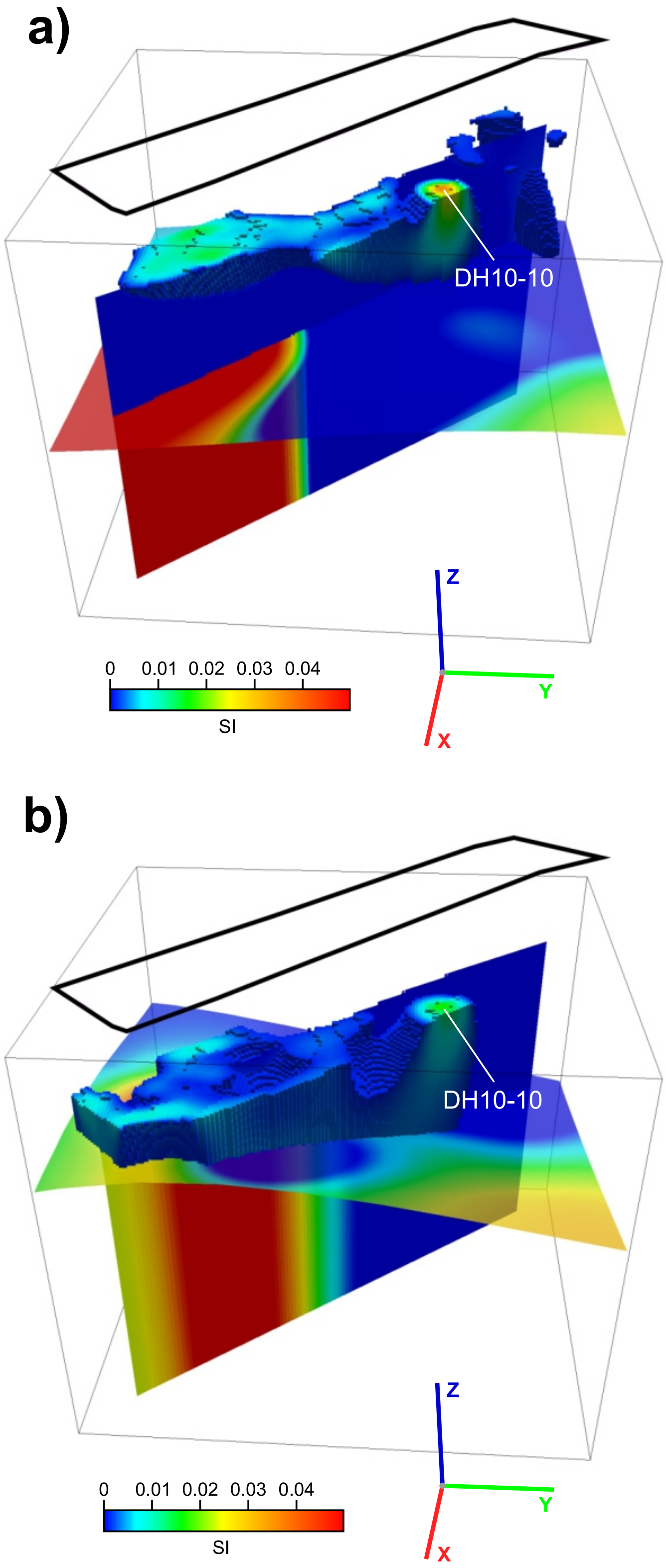

Fig. 8. Detail of high-resolution RPAS survey area (black) inverted high-resolution magnetic susceptibility model (SI). **a)** Data-poor model. **b)** Data-rich model. Top-of-bedrock surface coloured by bedrock magnetic susceptibility; cover values >0.0015 SI shown as blocks.

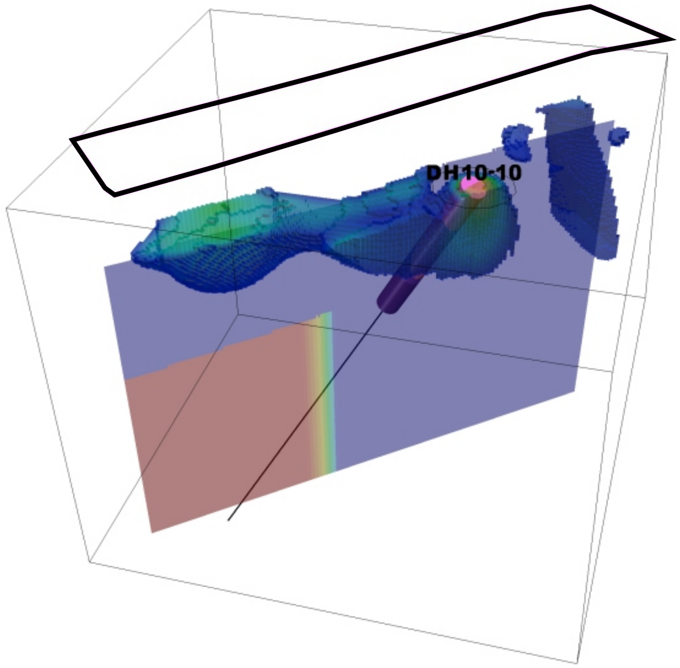

Fig. 9. Detail of high-resolution RPAS survey area (black) inverted high-resolution data-poor magnetic susceptibility model (SI); cover magnetic susceptibility values >0.0015 SI shown as blocks; with drill hole DH10-10.

low, over the surveyed area to establish the contrast required to separate a dispersal train from the bedrock signature below it. In the Deerhorn study area, we could not confidently separate the magnetic response of near-surface sediments, nor could we use RPAS magnetic data to supplement drift prospecting. More favourable bedrock geology with a high density of magnetic sources may help better define depth to bedrock and allow a more informed model. RPAS surveys designed to maximize areal coverage may also help produce a more usable product.

6. Conclusion

We collected RPAS-borne magnetic data at 13 locations in the Interior Plateau using a DJI Matrice 600 hexacopter and a GEM Systems DRONEmag magnetometer. Two surveys were flown over parts of the Deerhorn alkalic Cu-Au porphyry occurrence at the Woodjam Developed prospect; a low-resolution survey that collected data at 97.5 m above ground level with 100 m line spacing and a high-resolution survey that collected data at 10 m above ground level with 5 m line spacing.

We attempted to isolate the magnetic signature of surface sediments at Deerhorn from the underlying bedrock signature using these RPAS data in combination with regional magnetic, surficial geology, topography, and exploration drill hole data. RPAS surveys with larger areal coverage captured more magnetic features to provide improved constraints on sediment thickness and anomaly depth. However, complete separation of surface sediment and underlying bedrock magnetic signatures using RPAS data could not be accomplished. The magnetic depth to source analysis informs on the general cover thickness where magnetic anomalies are present, which can be an asset in the absence of drilling.

An exchangeable payload RPAS is an affordable and versatile platform for acquiring magnetic data from the air. Compared to traditional helicopter and fixed-wing aircraft platforms, RPASs can fly tighter line-spaced surveys with more consistent terrain clearance enabling detection of weakly magnetic surface sources. Surveys at a moderate height above ground with tight line spacing (e.g., 50 m above ground level at 10 m line spacing) over more magnetite-rich sediments may allow small shallow anomalies to be captured over larger areas to provide improved estimates of sediment thickness and greater isolation of the sediment component through three-dimensional inversion.

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