Uncovering Porphyry-Deposit Potential in the Quesnel Terrane of Central British Columbia Using Geology and 3-D Geophysics (Parts of NTS 093A, B, G, H, J, K, O)

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Introduction

The Quesnel terrane of British Columbia (BC) is well known in the mineral exploration community as a terrane that is well endowed in porphyry Cu-Au mineralization. Past-producing, currently producing and developed porphyry deposits are aligned the length of the Quesnel terrane, with an obvious, approximately 300 km gap in occurrences between the currently producing Mount Milligan and Mount Polley porphyry Cu-Au deposits (Figure 1). The overall high porphyry prospectivity to the north and south of this region suggests that new porphyry deposits are yet to be discovered within this gap. The reason for the lack of exploration and discovery in this area is the extensive Quaternary cover, which limits geological knowledge and discourages exploratory drilling.

A significant amount of geophysical data exists across this region, much of which has been collected and generated through previous Geoscience BC endeavours. The Geoscience BC QUEST project, in particular, led to the collection of valuable electromagnetic (EM) and gravity data (Barnett and Kowalczyk, 2008; Geotech Ltd., 2008; Sander Geophysics Ltd., 2008). Along with the existing country-wide Natural Resources Canada (NRCan) magnetic datasets (Natural Resources Canada, 2020), the available geophysical knowledge has the potential to provide insight into the geology of the drift-covered central Quesnel terrane. Geophysical data have been employed to various extents in past work to advance knowledge of geology and structure in central BC (Mira Geoscience Ltd., 2009; Siddorn, 2011; Sanchez et al., 2015). However, the value of the existing data and 3-D geophysical inversion models derived from these data has yet to be fully realized, with opportunities for more co-operative interpretation, integrating existing geological knowledge, still available.

This project, titled ‘Identification of New Porphyry Potential Under Cover in Central British Columbia’ and part of Geoscience BC’s Central Interior Copper-Gold Research series, has an area of interest that overlaps that of Geoscience BC’s former QUEST project but focuses specifically on the areas of more extensive overburden. Existing data from previous Geoscience BC projects and from NRCan are used to 1) model the overburden thickness through the most heavily covered portions of the Quesnel terrane; and 2) attempt to characterize and resolve a suite of geophysical anomalies that is consistent with hostrocks of porphyry deposits. Consolidating knowledge of overburden thickness and buried geology will help explorers know where to focus efforts and gain insight for future exploration, geophysical and geochemical survey design, and mine development.

Project Strategy

Gold-rich alkalic-porphyry deposits are a feature of BC geology (Lang et al., 1995; Chamberlain et al., 2007) and are genetically associated with oxidized magmas. Thus, the magmas contain abundant magnetite. In addition, alteration-mineral assemblages, notably those characterizing the potassic-alteration phases related to the hot, metal-rich fluids from the core of these porphyry systems, typically also contain magnetite (Chamberlain et al., 2007). These are positive features for geophysics-based porphyry exploration, since magnetic highs will be associated with alkalic-porphyry intrusions and their alteration haloes.

Logan and Schiarizza (2011) outlined two belts of alkalic intrusions in the southern Quesnel terrane. These alkalic intrusions, many of which have associated porphyry mineral occurrences and deposits, are strongly correlated with magnetic anomalies (Figure 2). Based on this observation, a suite of similar magnetic targets within the ‘gap’ between

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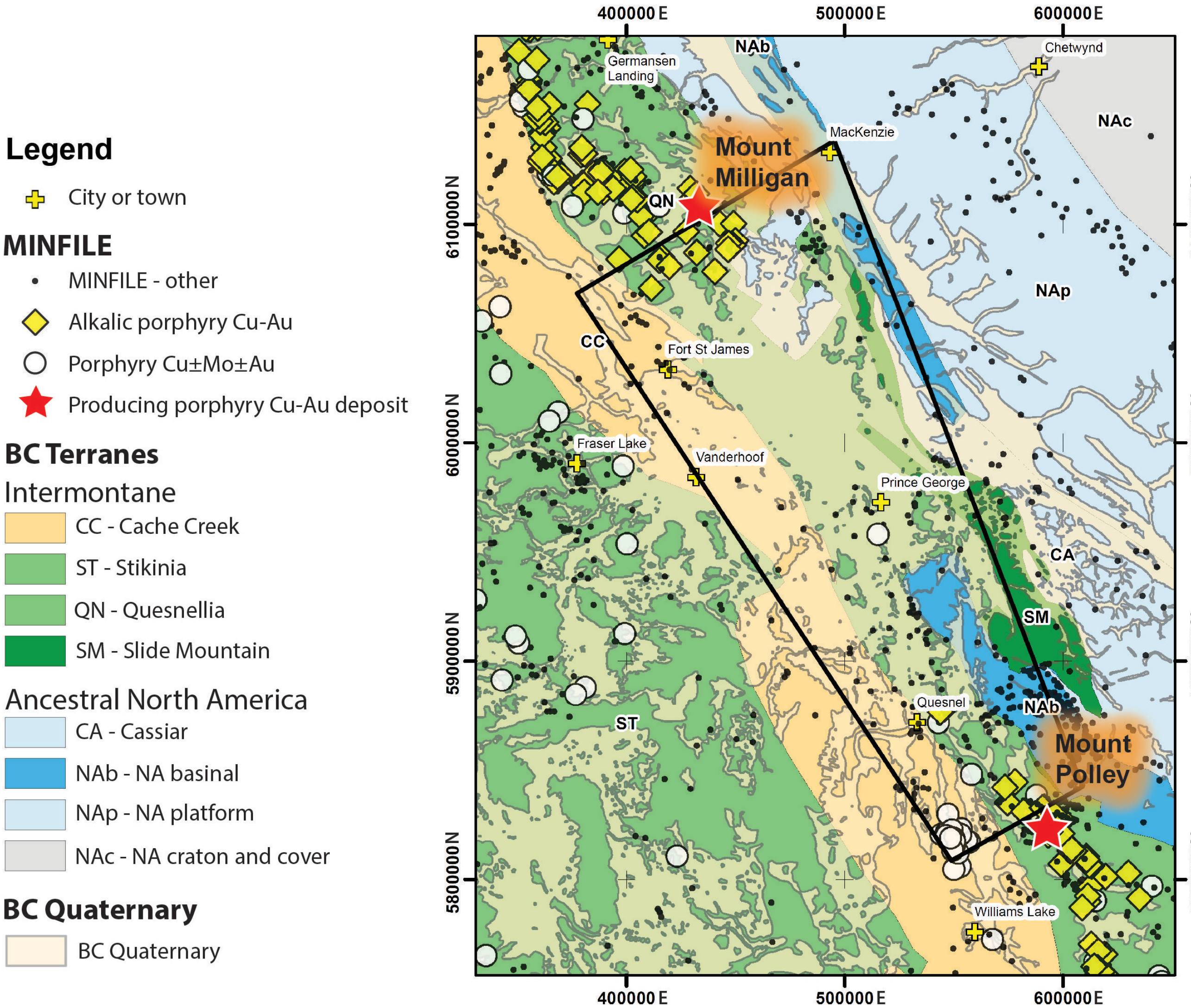

Figure 1. Project area overlain on the northern Cordilleran geological terrane map (Colpron and Nelson, 2011). Surficial geology indicating Quaternary overburden distribution through the region shown in pale transparent yellow (Cui et al., 2017). Locations of MINFILE BC (BC Geological Survey, 2020) porphyry occurrences shown as yellow diamonds (alkalic-porphyry Cu-Au occurrences) and white circles (porphyry Cu-Mo-Au occurrences). Project area outlined in black. Map co-ordinates in UTM Zone 10, NAD 83.

the Mount Milligan and the Mount Polley deposits was selected. These interpreted intrusive targets are the focus of this project, and their prospectivity as porphyry hosts or sources is followed up with consideration of regional overburden thickness and other geophysical and geological characteristics.

A new overburden-thickness model for the central Quesnel terrane is developed as part of this project. Surficial-geology maps, as well as drift-thickness models, have previously been completed in this region (Andrews and Russell, 2008; Maynard et al., 2010). These are based primarily on mapping and on existing BC groundwater-well databases. In the surficial maps, whose primary purpose is to map different types of surficial material, thicknesses are provided as broadly estimated ranges. Helicopter-borne Versatile Time-Domain Electromagnetic (VTEM™) data from Geoscience BC's QUEST project, and information from associated inversion models, have not been previously incorporated into these maps or models of overburden thickness. The inverted VTEM data provide the key control in developing an improved thickness model. The VTEM data significantly increase the regional coverage beyond populated regions where water wells are focused and into more heavily covered areas where thickness estimates from surficial mapping are less well constrained.

This paper focuses on preliminary selection of intrusive targets and modelling of overburden thickness using VTEM. The advances reported herein are steps toward a more in-depth investigation and final report on prospective porphyry environments in the Quesnel terrane, which will be released in 2021.

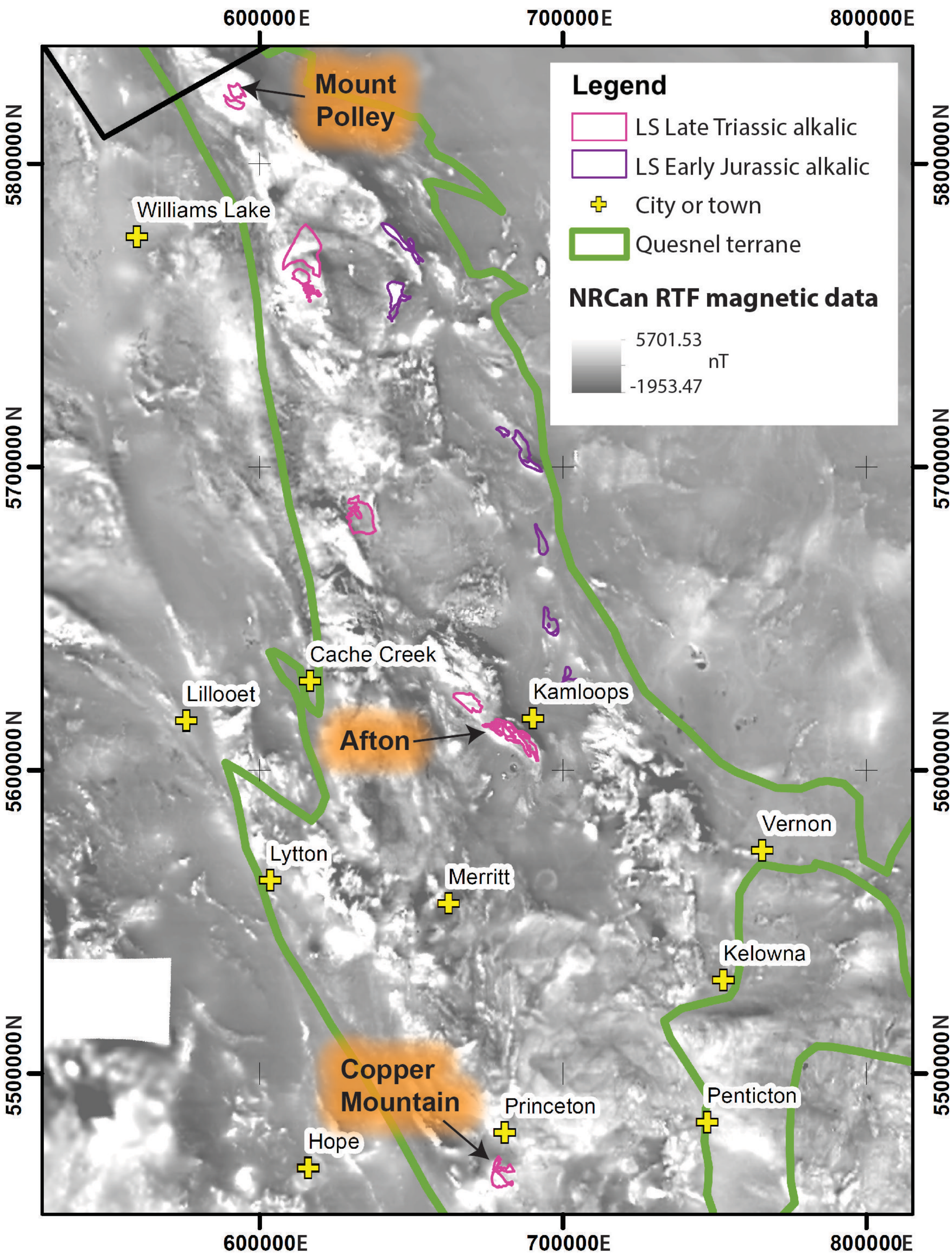

Figure 2. Alkalic-intrusive suites identified within the southern Quesnel terrane by Logan and Schiarizza (2011) are indicated by 'LS' in the legend. The western Late Triassic alkalic belt is shown in pink and the eastern Early Jurassic alkalic belt is shown in red. Several Cu-Au porphyry deposits are indicated, each of which is correlated with magnetic host or source intrusions. Background is NRCan residual-total-field magnetic data (Natural Resources Canada, 2020). The Quesnel terrane is outlined in green. Abbreviation: nT, nanotesla.

Identification of Intrusive Targets

The Natural Resources Canada (NRCan) residual-total-field data (Natural Resources Canada, 2020), as well as several derivatives of the magnetic data, were evaluated to identify magnetic anomalies that appear to be attributed to an intrusive source rock (Figure 3). Fifty-eight anomalies were chosen manually. The selection criteria required that the anomalies be somewhat rounded in shape, that they appear to crosscut stratigraphy or other geological bodies, and that they be of a size similar to intrusive bodies known to be related to the Mount Milligan and Mount Polley porphyry deposits. Comparisons between the magnetic data and bedrock geology maps confirm that some of the volcanic stratigraphy within the Quesnel terrane's Nicola and Takla groups, as well as ultramafic units of various ages, are magnetically anomalous. Positive magnetic anomalies clearly attributed to mapped mafic to ultramafic rock types were avoided.

The magnetic anomalies chosen range in size from approximately 2 km^2 to 50 km^2. Some are coincident with intrusive rocks that are mapped at the surface, whereas others do not have an obvious link to mapped or interpreted bedrock geology and may therefore represent a deeper, or undercover, magnetic body. The magnetic targets can be subdivided roughly into four clusters: 1) east and north of Quesnel, where several smaller anomalies are aligned with the regional northwest geological strike; 2) south of Prince George, where 3 to 4 anomalies occur along an east-west trend; 3) north of Prince George, where a north-northeast trend is apparent; and 4) east of Fort St. James, where the cluster of anomalies strikes northwest again.

Overburden-Thickness Modelling

Overburden-thickness modelling was undertaken to improve on current knowledge of the distribution and thickness of surficial geological material across the central Quesnel terrane. Such information is critical to improving target ranking and exploration decision-making. Overburden modelling also provides a constraint for the eventual modelling of selected magnetic anomalies of interest using geophysical inversions. The overburden-thickness model can provide an upper constraint on the location of the tops of magnetic geological bodies in the subsurface.

The VTEM data for the region were collected by Geotech Ltd. in 2008 for Geoscience BC as part of the QUEST program (Geotech Ltd., 2008). This survey collected more than 11 600 line-km of data along east-west lines at a line spacing of 4 km. Following collection, the data were inverted in 1-D and the inversion results concatenated along-line to generate conductivity models along each survey line (Mira Geoscience, 2009). It has been recognized previously that QUEST VTEM conductivity models identify the presence of conductive overburden (Kowalczyk et al., 2010) and this was, in fact, one of the purposes of running the QUEST VTEM survey. Although the nature of the surficial materials that constitute overburden in this part of BC is highly variable and some are likely more electrically conductive than others, the extent of mapped surficial material correlates well with conductive layers resolved in inversions of the VTEM data.

The VTEM inversion sections and thickness-model data constraints were compiled using the 3-D geological modelling software SKUA-GOCAD (Figure 4). The complete list of data used to constrain the current overburden-thickness model is provided in Table 1.

To confirm independently whether VTEM models could resolve the thickness of the overburden, VTEM line inversions were compared with information from water wells, exploration drillholes and outcrop databases at localities where these data co-occur. The bases of thin near-surface conductors were found to regularly match the bottom of overburden recorded in water-well and exploration drill logs. The thin conductive overburden layer is commonly absent in areas of known outcrop. Figure 5 illustrates examples of correlation between various constraining data and conductivity horizons interpreted to represent overburden.

Two types of overburden-thickness constraints are extracted from VTEM inversions: 1) base of conductive overburden, and 2) locations of no apparent overburden. Interpretations of the apparent base of the overburden were manually digitized line by line. For each line that was interpreted, only those conductors that were most obviously related to overburden were marked. Other conductivity anomalies that had several possible geological, geographic or cultural causes, or were ambiguous, were ignored. Interpretations were consistently checked against groundwater-well and exploration-drillhole data, where available. Once interpretations were complete, all constraints were converted to a 3-D pointset in SKUA-GOCAD.

All constraints were given equal weighting or importance in the model. A 3-D surface was warped to the point constraints to create a new surface that represents the base of overburden. The interpolation was done in SKUA-GOCAD, using discrete smooth interpolation (DSI). On a first attempt in areas of higher or more abrupt relief, the surface was pulled away (down) from the topographic 'peaks' due to smoothing during interpolation. Points were then added manually by digitizing topographic peaks in SKUA-GOCAD, and a second attempt at warping the surface with these additional constraints succeeded in reducing that pull-down effect. In several places, the base of overburden surface was inadvertently smoothed between topographic highs, causing it to sit above the true topographic surface. The base of overburden surface was then simply pushed

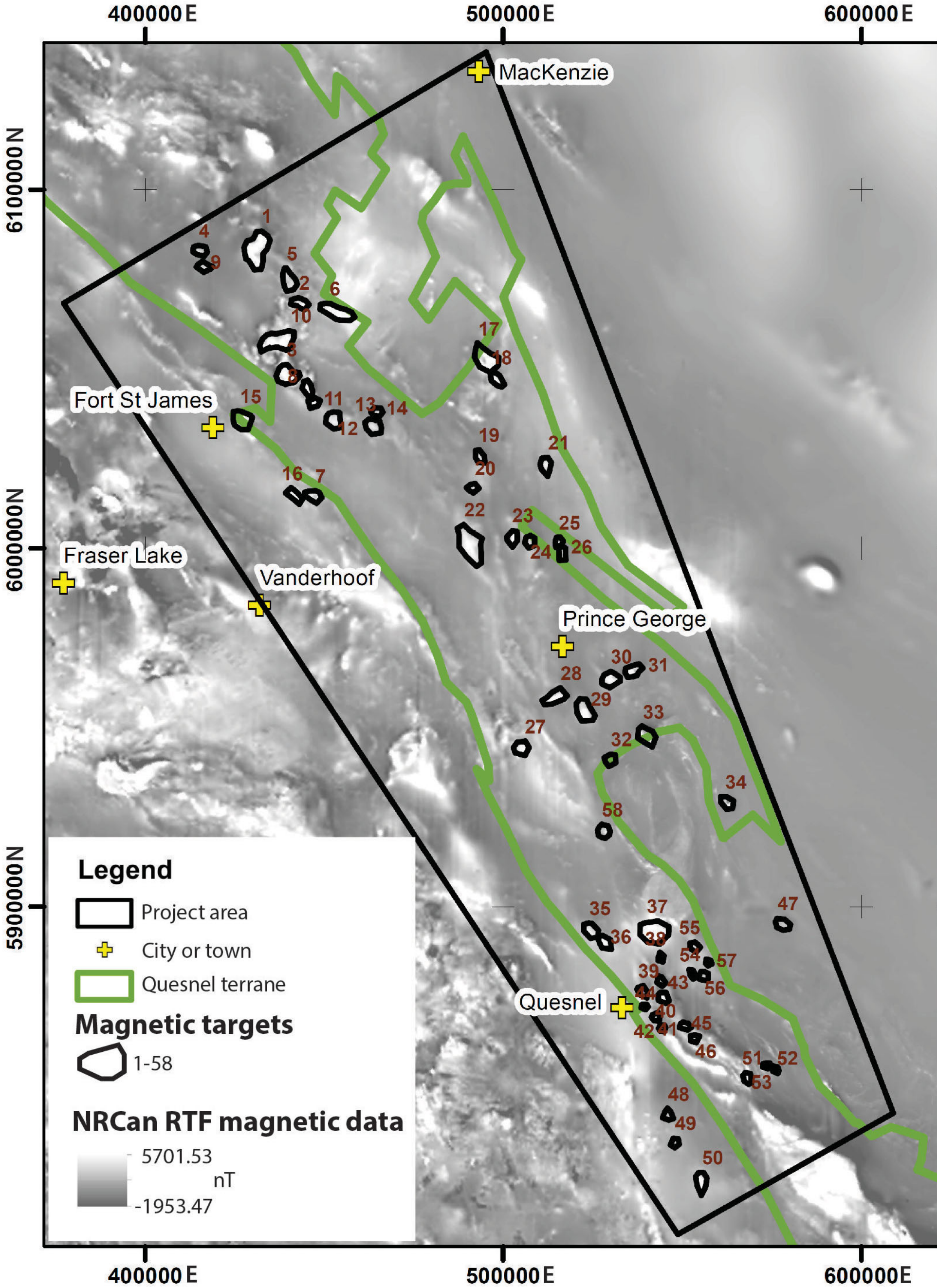

Figure 3. Magnetic targets selected for investigation (outlined in black; n = 58) superimposed on the Natural Resources Canada residual-total-field magnetic data grid (Natural Resources Canada, 2020). The Quesnel terrane is outlined in dark green, and the project area lies within the black quadrilateral. Abbreviation: nT, nanotesla.

down everywhere that it occurred above topography using the surface-modelling tools in SKUA-GOCAD.

The results (Figure 6) were reviewed and checked against the constraints to ensure that the constraints continued to honour, within a reasonable margin of error, the surface interpolation.

There is a good spatial correlation between the extents of mapped Quaternary geology and areas of modelled cover material (Figure 6). The addition of detailed constraints from VTEM interpretations results in more detail about overburden thickness in areas that are difficult to access for mapping, and gives a sense of the significant variability in thickness through the region. The model indicates that there are likely more 'windows' of thin to no overburden than indicated on regional Quaternary geology maps. These areas of thinner cover might provide easier access to

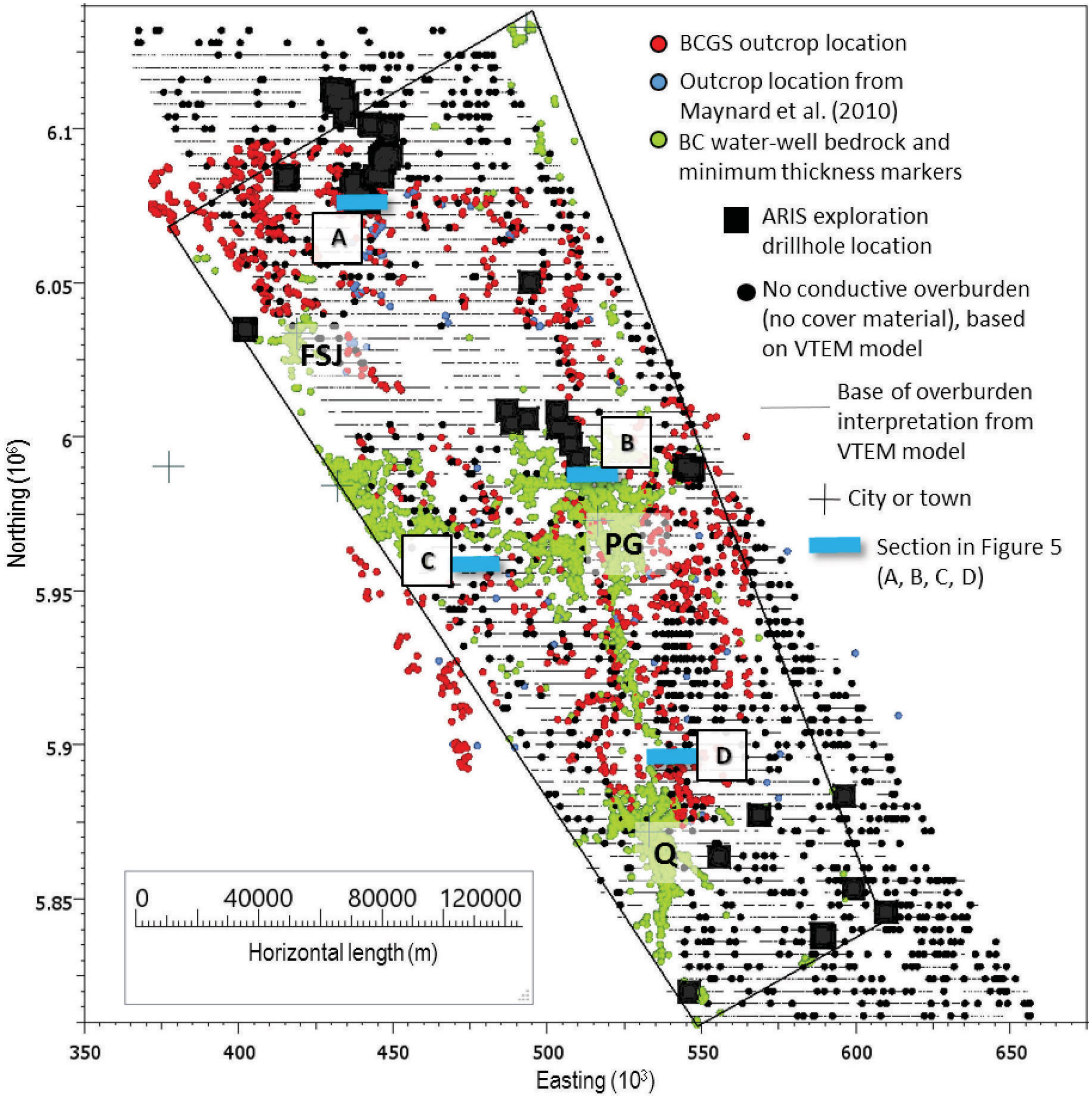

Figure 4. Constraining data used for overburden-thickness modelling. Constraining data from VTEM inversion models are derived from interpretations digitized along line on east-west VTEM lines spaced 4 km apart. Project area lies within the black quadrilateral. Abbreviations: PG, Prince George; FSJ, Fort St. James; Q, Quesnel.

bedrock for mapping and exploration purposes than previously thought.

Based on this model, the overburden thickness ranges from 0 to 297 m and averages 36 m. Most of the magnetic targets identified for this project occur beneath <50 m of overburden according to the model. The thickest overburden areas, with >200 m modelled thickness, occur south of Prince George, about 40 km northwest of Prince George, and in the northernmost part of the project area.

Preliminary Geophysical Characterization of Magnetic Targets

The goals of geophysical characterization of selected targets are to 1) determine if other geophysical data or models in addition to magnetics can help uniquely identify felsic to intermediate intrusive rocks; 2) assess the variability of geophysical signatures of interpreted intrusive rocks; and 3) determine whether differences between the geophysical fingerprints of interpreted intrusive rocks are relevant to

Table 1. Types and numbers of data constraints used for overburden-thickness modelling in this project.

Constraining data	Number of data points	Source
Groundwater wells:		BC Ministry of Environment and Climate Change Strategy (2020)
Bedrock interface	1169	
Minimum thickness where bedrock not recorded	5924	
Exploration drillhole data from BCGS assessment reports:		BC Ministry of Energy, Mines and Low Carbon Innovation (2020)
Bedrock interface	198	
Minimum thickness where bedrock not recorded	30	
Outcrop location:		Logan et al. (2010), Maynard et al. (2010)
BC Geological Survey	1225	
work by Maynard et al. (2010)	95	
QUEST program VTEM model interpretations:		This study
Points digitized from base of overburden interpretations	25965	
Points digitized from areas of no apparent overburden	1047	

porphyry prospectivity. To gain further insight into the geology of the chosen magnetic targets, a preliminary assessment was made of the regional density and resistivity character of the magnetic targets.

A review of existing rock-property data from the Quesnel terrane (Enkin, 2018) suggests that felsic to intermediate intrusive rocks, like those known to host or otherwise be genetically related to Cu-Au porphyry deposits in BC, should be characterized by high resistivities and low to moderate densities (Figure 7). This makes sense because a massive igneous body like an intrusion should be electrically resistive. Felsic to intermediate rocks will have lower densities than mafic to ultramafic rocks due to their higher proportion of low-density silicate minerals, but should have higher densities than sedimentary rocks, which typically have higher porosity. These characteristics should distinguish them from lower density, higher conductivity sedimentary or volcano-sedimentary rocks, and very high density, massive mafic and ultramafic rocks. Secondary alteration of rocks can lead to changes in rock properties along localized fluid pathways (Mitchinson et al., 2013), but the bulk overall rock response should prevail in the cases of these coarse regional datasets.

The density and resistivity for each chosen magnetic target was sampled from the gravity inversion (Mira Geoscience Ltd., 2009) that modelled QUEST regional airborne-gravity data (Sander Geophysics Ltd., 2008), and from a new 3-D interpolated VTEM conductivity model (this project). The density data were sampled from an inversion depth slice at 125 m and the VTEM conductivity model (converted to resistivity) was sampled from a 160 m inversion depth slice (Figure 8). Sampling the data at depth removes some of the influence of surficial rocks on the model, meaning that the signature should be bedrock driven.

Density and resistivity data were 'painted' onto point sets that were created for each magnetic target using SKUA-GOCAD. In addition, points were extracted that coincide with the British Columbia Geological Survey bedrock geology polygons for intrusions related to the Mount Milligan and Mount Polley deposits, and these were also 'painted' with QUEST density and resistivity. Box and whisker plots showing the ranges of inversion-derived density and resistivity for the Mount Milligan and Mount Polley intrusions, and for the 58 magnetic targets, are shown in Figure 9.

Intrusions associated with Mount Milligan and Mount Polley have densities that are moderate compared to the full density dataset that would represent the densities of the varied geology across the QUEST project area. This is consistent with the types of intrusions known to host or be the source of alkalic-porphyry deposits in the Quesnel terrane. Almost all of the selected magnetic targets fall into the same range of moderate densities. Future analysis will attempt to discern the factors that led to the slightly higher densities characteristic of Mount Milligan and the slightly lower densities characteristic of Mount Polley, and whether these factors may influence prospectivity of the source rocks.

The Mount Milligan and Mount Polley intrusions have moderate to high resistivities relative to the full resistivity dataset, as expected from rock properties of felsic to intermediate intrusive rocks. The 58 magnetic targets display a large range of resistivities, with only a subset reaching the higher values seen for Mount Milligan and Mount Polley intrusive rocks. Again, future work will consider additional geological and geophysical data layers, with the goal to expand on what the variability in resistivity between these targets reveals about their geology and prospectivity.

Ongoing Work

The overburden-thickness model will be refined and updated in the final report for this project. Two approaches will be pursued to refine the model. The first addresses the 'pulling down' of the base-of-overburden surface during

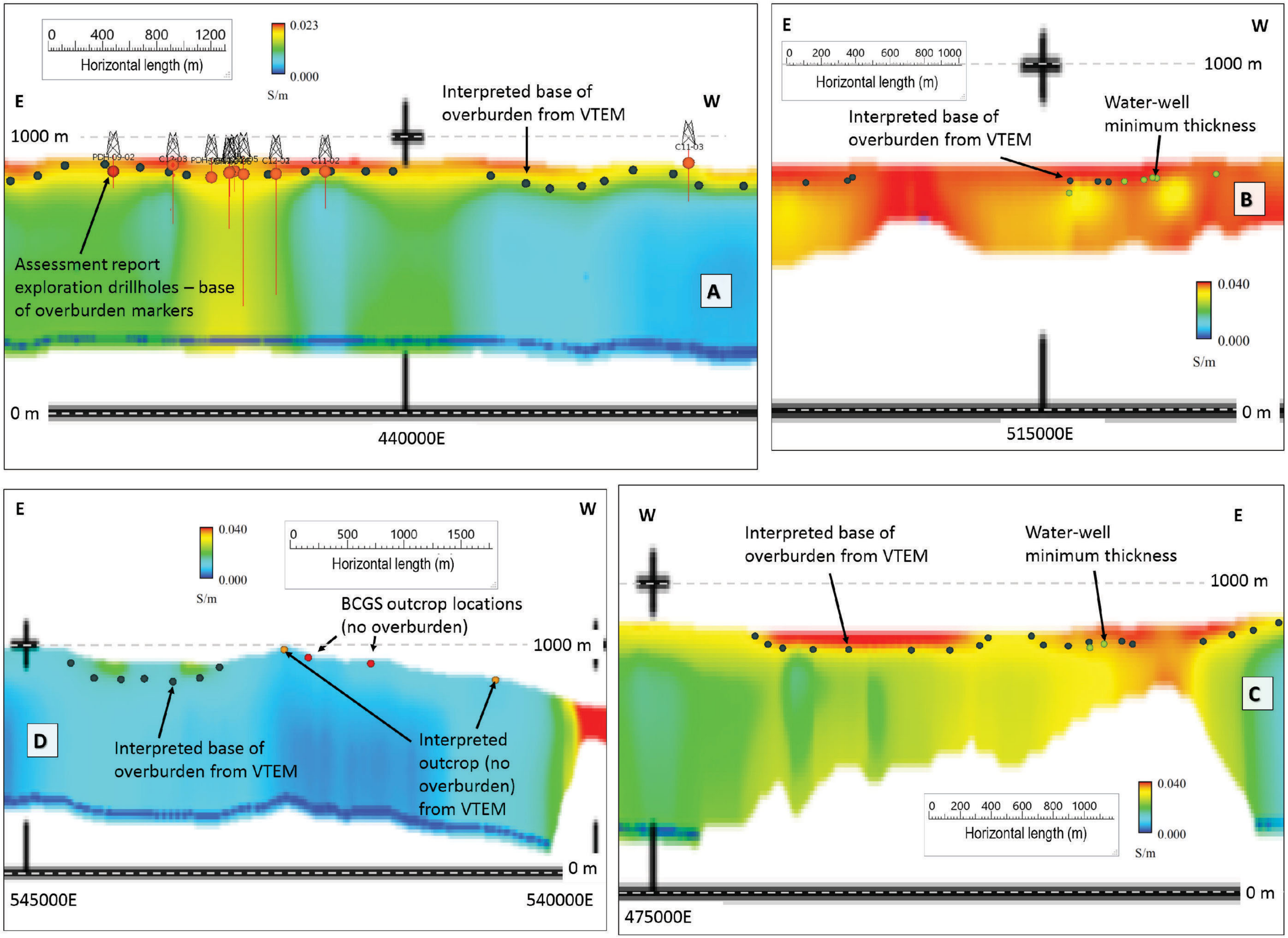

Figure 5. Vertical cross-sections through VTEM conductivity inversions showing correlation between high-conductivity layers resolved near surface and the presence of overburden as indicated in exploration-drilling, water-well and outcrop data. Vertical scale is elevation with 2x exaggeration. Section locations A–D are shown in Figure 4. Abbreviation: S/m, siemens/metre.

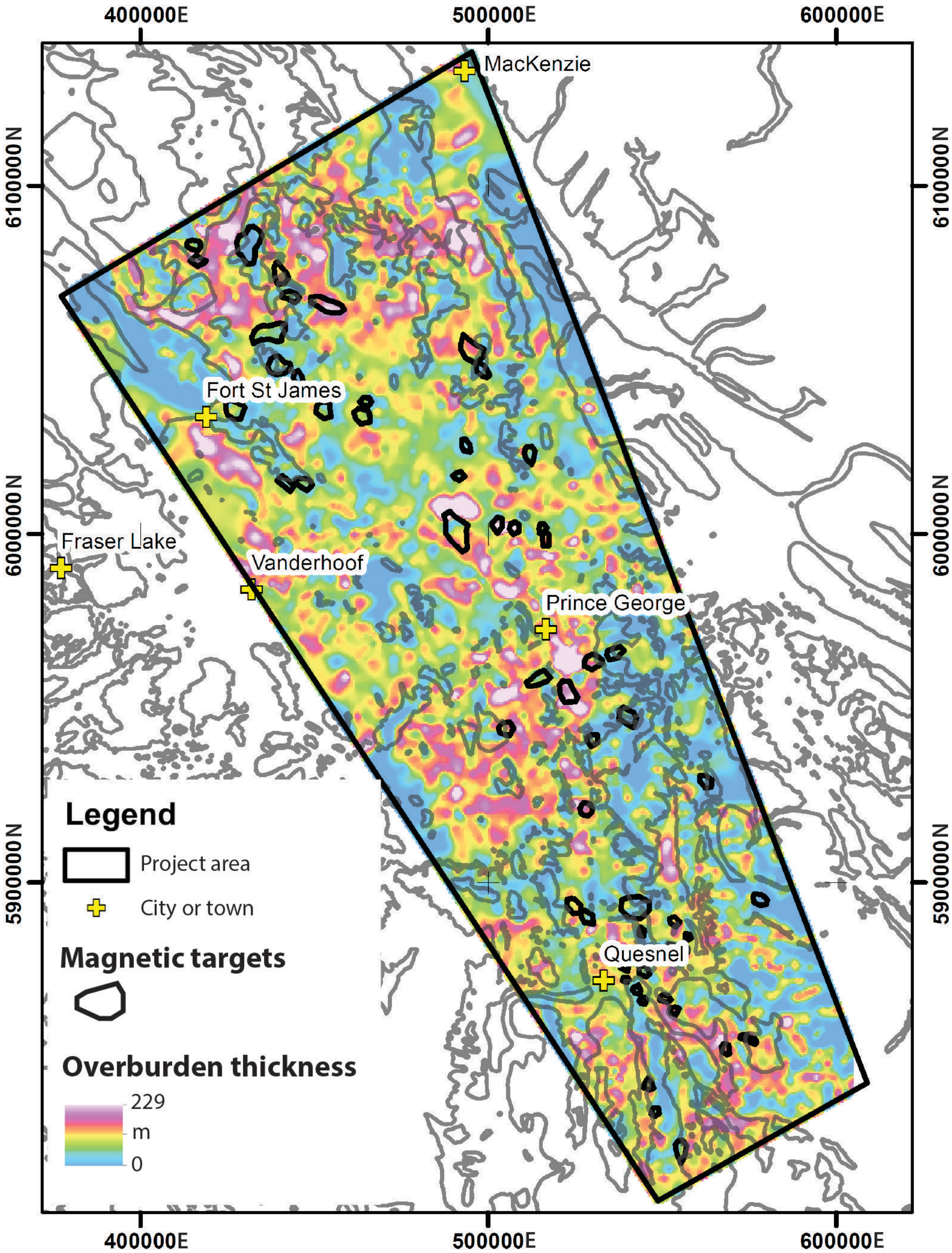

Figure 6. Overburden-thickness model of the project area. Quaternary geology (Cui et al., 2017) shown in dark grey outline.

interpolation. Rather than using manually picked topographic peaks to draw the surface back up to the likely uncovered topographic highs, an attempt will be made to use contours mapping the base of alpine physiography as a hard constraint above which overburden will be removed. The second refinement will focus on an improved interpolation to reduce any 'line effects' where VTEM inversion interpolations are exerting a concentrated control on the base of the overburden surface. The final thickness model will be available as both a 3-D surface (DXF and GOCAD surface objects) and as a 2-D grid (ASCII) recording depth to the base of overburden.

Work on geophysical classification of key magnetic targets will continue and include comparisons to geophysical responses associated with other known porphyry-related intrusions north and south of the project area (north and south Quesnel terrane). An updated gravity inversion will be completed using the overburden-thickness model to refine the bedrock-density estimates. An additional VTEM inver-

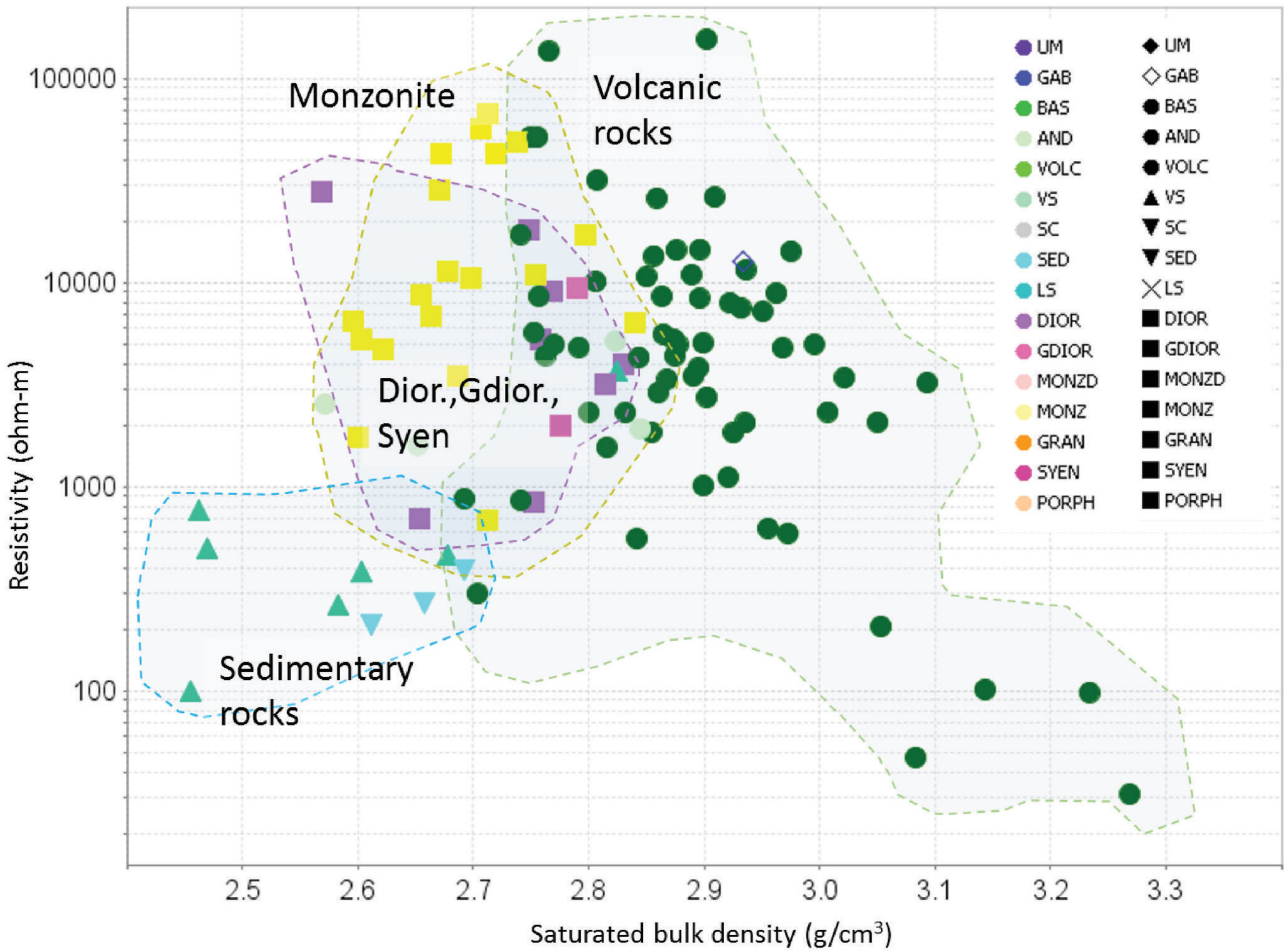

Figure 7. Saturated bulk density versus resistivity of rocks from the Quesnel terrane. Data from the Canadian Rock Property Database (Enkin, 2018). Legend shows colour and shape assigned to each rock type. Abbreviations: Ω-m, ohm-metres; AND, andesite; BAS, basalt; DIOR, diorite; GAB, gabbro; GDIOR, granodiorite; GRAN, granite; LS, limestone; MONZ, monzonite; MONZD, monzodiorite; PORPH, porphyritic intrusive; SC, schist; SED, sedimentary rock; SYEN, syenite; UM, ultramafic; VOLC, volcanic rock; VS, volcanic sediment.

sion, deriving induced-polarization effect, will be run to generate a model that provides information about the chargeability of rocks across the QUEST project area.

Petrographic, lithogeochemical and petrophysical studies are underway on a set of samples from the project area. The goal of these analyses is to determine whether these properties can be used to further prioritize chosen magnetic targets.

The most prospective interpreted intrusive targets chosen on the basis of geophysical and geochemical characterization will be modelled in 3-D using magnetic inversions to provide details on their shape, size, depth and magnetic properties. This information will further inform mineral explorers on the physical parameters of the target, which will help guide prospecting, planning of local geochemical and geophysical surveys, and drilling.

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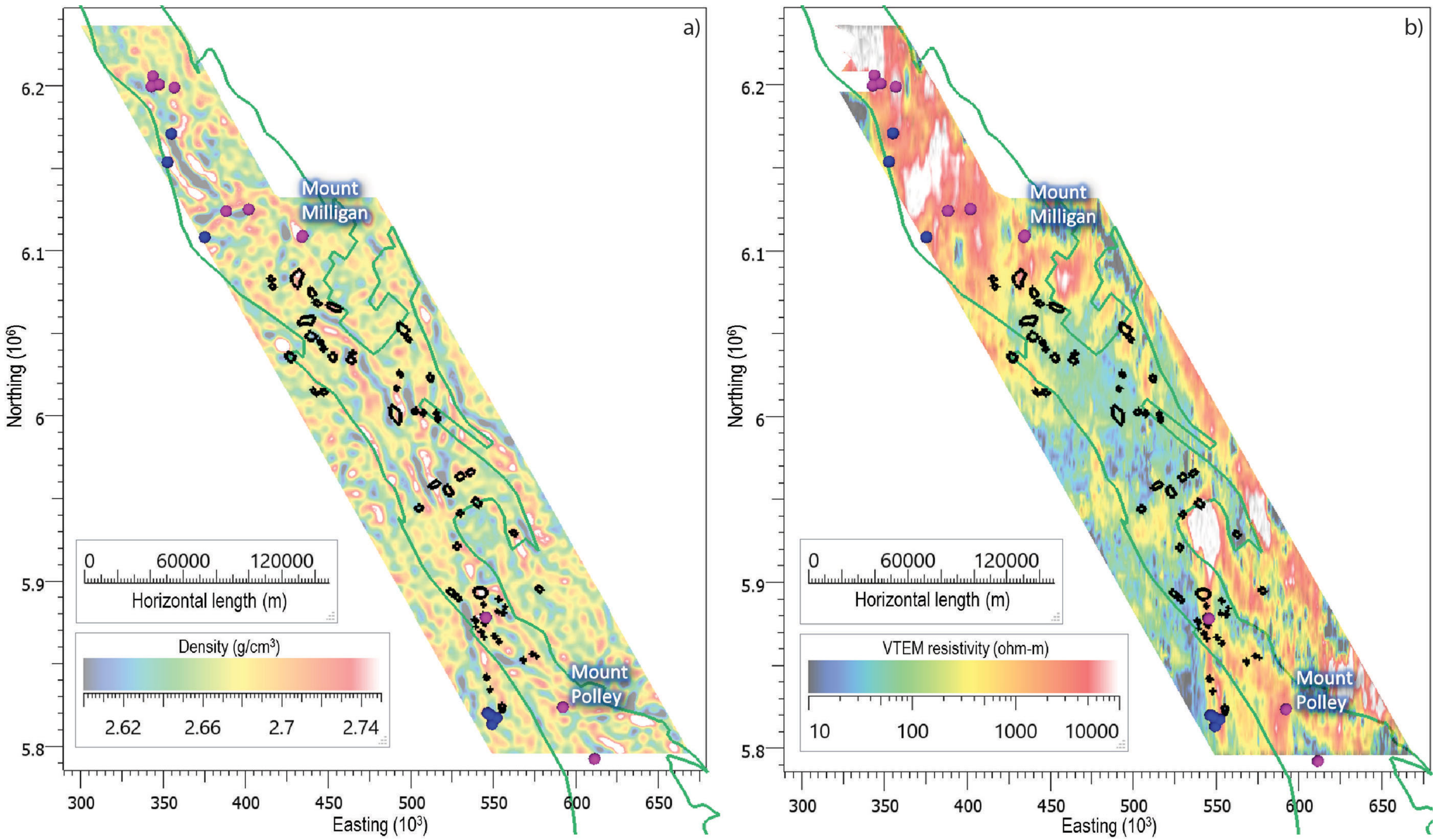

Figure 8. a) QUEST density model at 125 m depth, and **b)** QUEST VTEM resistivity model at 160 m depth, used to identify density and resistivity character of selected magnetic targets. Quesnel terrane outline in green. Pink dots represent alkalic Cu-Au porphyry deposits and blue dots represent other porphyry-deposit types.

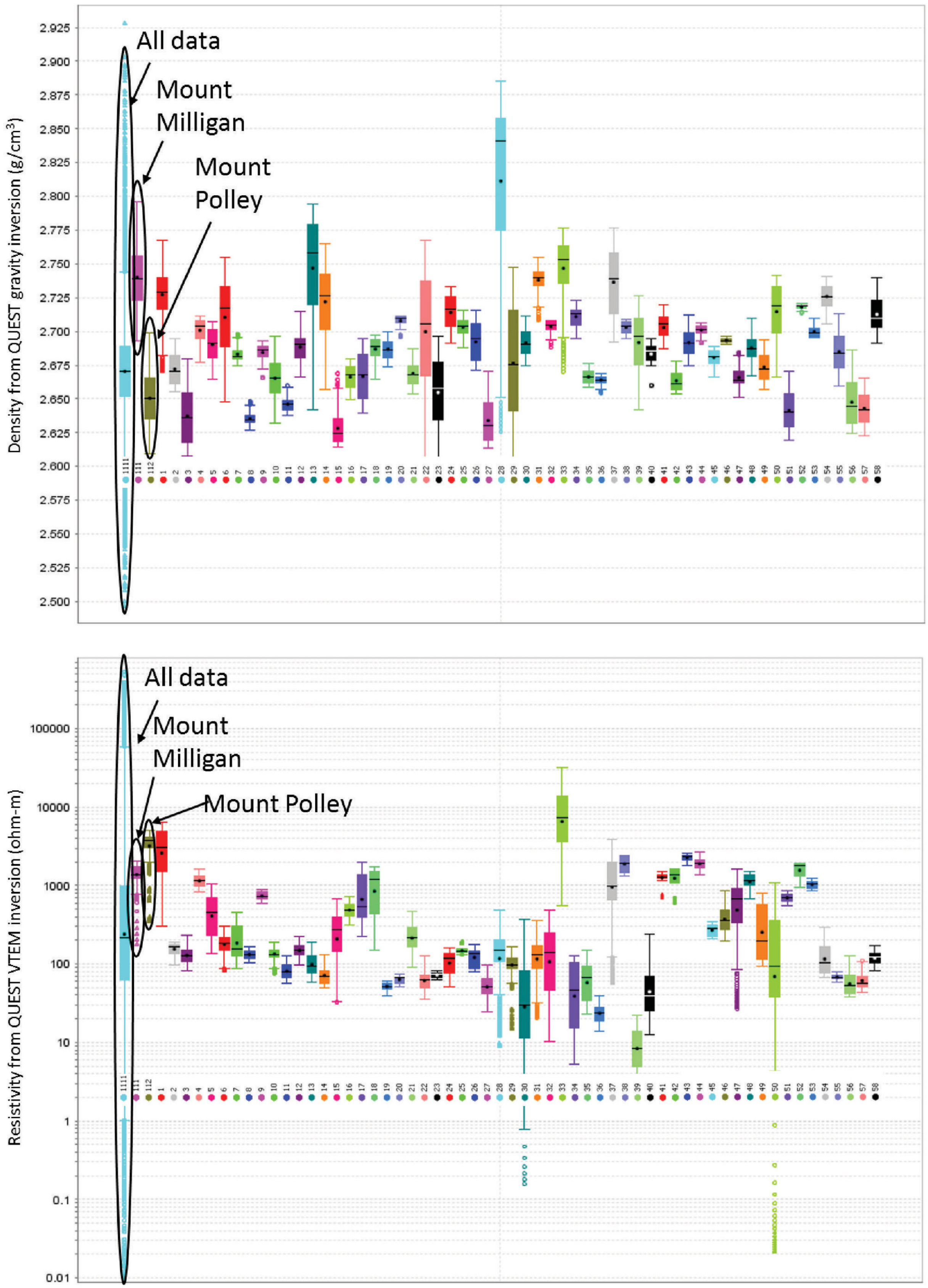

Figure 9. Density (upper plot) and resistivity (lower plot) ranges for each of the 58 magnetic targets (colors assigned randomly) sampled from regional gravity and VTEM inversions, compared to density and resistivity ranges for the entire QUEST project area and those associated with the Mount Milligan and Mount Polley intrusions.

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