Integrated Interpretation of Electromagnetic and Gravity Data to Resolve Deep Geology and Aid Mineral Exploration in the Quesnel Terrane, Central British Columbia (Parts of NTS 093A, B, G, H, J, K, N, O, 094C, D)

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Introduction

A nearly 300 km swath of the central Quesnel terrane of British Columbia (BC) is covered by glacial till deposits (Figure 1). With limited direct access to bedrock for mapping, geology is largely inferred here. This makes it difficult to confidently link geological formations along the terrane, to unravel geological history and environments, and to fully understand the mineral potential of the region. One of the best means of mapping geology beneath this till cover is through collection and analysis of geophysical data. Previous geophysical-data interpretations for this region have relied mostly on magnetic data, which provides significant insight into bedrock lithology and structure. Magnetic surveys, however, respond only to rocks that contain magnetic minerals. Other geophysical methods may distinguish between lithological units where magnetic data cannot. Electromagnetic (VTEM) and gravity data collected for Geoscience BC's QUEST Project in 2007 have been underused to interpret geology of the Quesnel terrane beneath cover, yet show promise for distinguishing between volcanic units and identifying intrusive rocks (magnetic or nonmagnetic) and structure. This project aims to explore and define the ability of VTEM and gravity data to distinguish lithological units beneath cover in the Quesnel terrane, and to corroborate features interpreted previously from magnetic data. The project addresses two Geoscience BC Strategic Plan objectives:

- Advancing Science and Innovative Geoscience Technologies: The project will explore whether new geological information can be derived from underused electromagnetic and gravity data.
- Identifying New Natural Resource Opportunities: The project will provide further insight into geology beneath cover and, by association, mineral-deposit environments in the Quesnel terrane.

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Background

Quesnel Terrane Geology and Mineral Deposits

The Quesnel terrane is a volcanic-arc terrane of the Canadian Cordillera that formed between the Late Paleozoic and the Mesozoic, amalgamating onto the western edge of the ancestral North American craton (Nelson and Colpron, 2007). The geology of the terrane is dominated by mafic volcanic, volcaniclastic and sedimentary rocks and subduction-related intrusive bodies that are found exposed all along the north-striking terrane. Volcanic flows of Eocene to Pleistocene age blanket the Mesozoic geology in parts of the belt (e.g., Chilcotin Group rocks; Mathews, 1989).

British Columbia is a significant producer of Canada's copper (Natural Resources Canada, 2021), with most of the output coming from the province's porphyry-copper deposits. Porphyry-copper and -gold mineralization in the Quesnel terrane are known to be linked to magmatic events that correlate with the late development of the terrane. Specifically, four belts of intrusive rocks associated with porphyry mineralization have been identified in the southern Quesnel terrane, ranging in age from Late Triassic to Early Jurassic (Logan and Schiarizza, 2011; Logan and Mihalynuk, 2014). Alkalic porphyry deposits, known to be associated with two of the identified magmatic belts in the Quesnel terrane, are of particular economic interest due to their elevated abundances of gold and platinum-group metals (Jensen and Barton, 2000; Thompson et al., 2001; Hanley et al., 2020). Alkalic porphyry deposits currently being mined in the Quesnel terrane include the Mount Milligan, Mount Polley, New Afton and Copper Mountain deposits. Other notable developed porphyry properties include the Lorraine and Mouse Mountain properties.

In the central Quesnel terrane, there is excellent potential for porphyry mineralization similar to known occurrences in the northern and southern parts of the terrane; however, there is limited bedrock exposure due to overlying till deposits. Much of the geological understanding of the Quesnel terrane is derived from its northern and southern extents, where there is more topographic relief, less cover

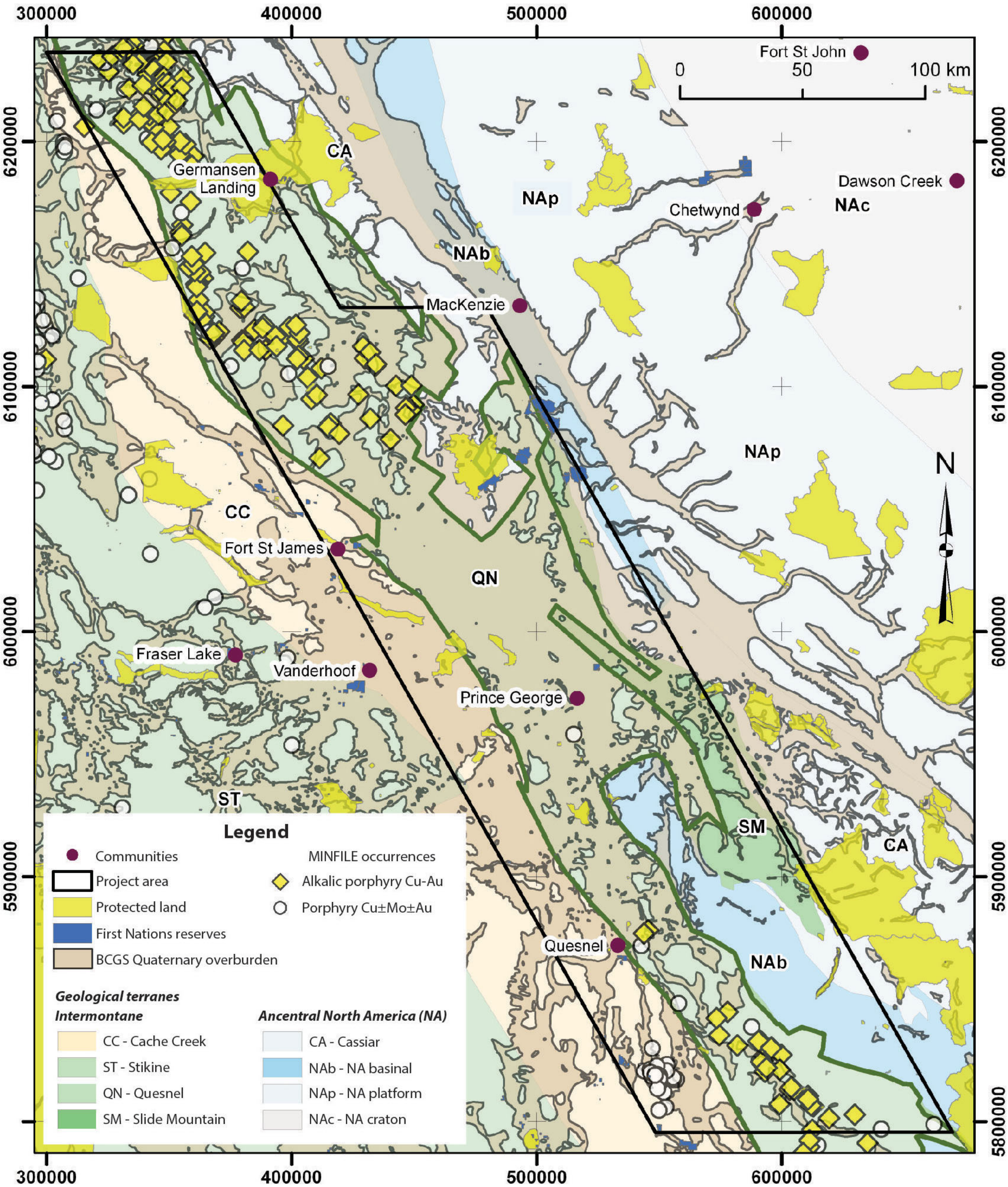

Figure 1. The study area for this project corresponds to Geoscience BC's QUEST Project study area. The light-brown region shows the distribution of Quaternary overburden mapped by the BC Geological Survey (Cui et al., 2017). Significant porphyry copper±gold±molybdenum and porphyry copper-gold occurrences are known in the northern and southern extents of the project area. Bedrock geology is largely obscured in the region around Prince George, limiting understanding of the full mineral potential of the central Quesnel terrane. Project area outlined in black. Quesnel terrane outlined in dark green. Locations of porphyry and other mineral occurrences from MINFILE BC (BC Geological Survey, 2020). Map co-ordinates in UTM Zone 10, NAD 83.

and better outcrop exposure. Recently, Quesnel terrane stratigraphy in the Bridge Lake–Quesnel River area of south-central BC was detailed by Schiarizza (2019). These detailed stratigraphic studies are used, in part, to guide understanding of geophysical patterns explored in this project.

Previous Geophysical Investigations in the Quesnel Terrane

There has been significant interest in improving knowledge of bedrock geology through the central Quesnel terrane due to its high mineral prospectivity. The best means of imaging the subsurface where there is surficial cover limiting direct geological observation is through remote sensing. Gravity and VTEM surveys over the most heavily till-covered regions of the Quesnel terrane were commissioned by Geoscience BC in 2007 (Geotech Limited, 2008; Sander Geophysics Limited, 2008), enhancing opportunities to discover new information about the subsurface of this terrane. Mira Geoscience Ltd. completed 1-D to 3-D geophysical inversions of the QUEST electromagnetic, gravity and magnetic data, and ran cluster analyses on the resulting models to identify geophysical domains.

A geological and structural interpretation for the central Quesnel terrane, using primarily magnetic data, was completed by Sánchez et al. (2015). Mitchinson et al. (2022) also evaluated Quesnel magnetic data, along with gravity and electromagnetic data, specifically to target intrusive rocks that could act as hosts to porphyry deposits in the Quesnel terrane.

Data and Methodology

Public Data Available

This study focuses on gravity and VTEM data collected as part of Geoscience BC's QUEST Project (Barnett and Kowalczyk, 2008). These data have not been widely used in interpretations of bedrock geology of the Quesnel terrane, yet geological information is represented in the data.

Gravity data were collected by Sander Geophysics (Sander Geophysics Ltd., 2008) at a survey-line spacing of 2 km. The data were inverted by Mira Geoscience (Mira Geoscience Ltd., 2009), and more recently by the University of British Columbia Geophysical Inversion Facility (UBC-GIF) as part of Geoscience BC's 'Identification of New Porphyry Potential Under Cover in British Columbia' Project (Mitchinson et al., 2022). Gravity-data maps and 3-D models of density can be used for geological interpretations (Figure 2a). Gravity 2-D–gridded data have cell sizes of 250 m^2 and inversion-model cell sizes of 500 m^2 near surface, so these data are best suited to interpreting regional trends in geology.

Electromagnetic data were collected by Geotech (Geotech Ltd., 2008). Survey lines were spaced 4 km apart, with data collected along the line every 0.1 second, which equates to a reading approximately every 2–3 m. These data were inverted by Mira Geoscience (Mira Geoscience Ltd., 2009). The inversion process involved completing 1-D inversions at each data point and then stitching the 1-D inversions together along the line to yield a pseudo–2-D inversion. With frequent along-line data, there is detailed information along a data transect and in the recovered inversion models. The 4 km distance between VTEM lines makes high resolution, between-line interpolation unreliable. However, even with the more detailed information lost, generation of isosurfaces from inversion models can still reveal broad trends in resistive and conductive domains that are useful for regional interpretation (Figure 2b).

In addition to gravity and VTEM data and models, Natural Resources Canada magnetic data (Natural Resources Canada, 2020) will be evaluated. Rock lithological, lithogeochemical and physical property data were sourced from the BC Geological Survey (BCGS; Han et al., 2016; Cui et al., 2017; BC Ministry of Energy, Mines and Low Carbon Innovation, 2020) and the Geological Survey of Canada (Enkin, 2018). Rock-type information derived from the geochemical and petrophysical databases are especially useful for linking geophysical responses to observed bedrock geology. To utilize the rock descriptions from public physical-property and geochemical datasets, which are often very detailed and/or not standardized, a simplified lithological code consistent across databases was established for broad-scale integration against the geophysical data.

Interpretation products from Barnet and Williams (2009), Fraser and Hodgkinson (2009), Mira Geoscience (2009) and Sánchez et al. (2015) will also be used in this work, to compare previous interpretations to new interpretations from VTEM and gravity data.

Methodology

Geophysical data and models were compiled in 3-D GIS platforms SKUA-GOCAD™ and Geoscience Analyst Pro. BC Geological Survey geology maps and other relevant data, including drilling, sampling and geochemical databases, that provide direct observations about bedrock geology, were imported into 3-D software for exploratory data analysis and preliminary identification of correlations between geophysical and geological data.

Initial observations indicated that VTEM inversions provide information about geological structure and texture. Guided by these observations, geological interpretations were made along each VTEM inversion line. Specifically, resistive bodies reflecting cohesive intrusions and massive volcanic deposits were digitized. Apparent faults and contacts were also identified as vertical or dipping conductors. VTEM model trends correlate extremely well with gravity-

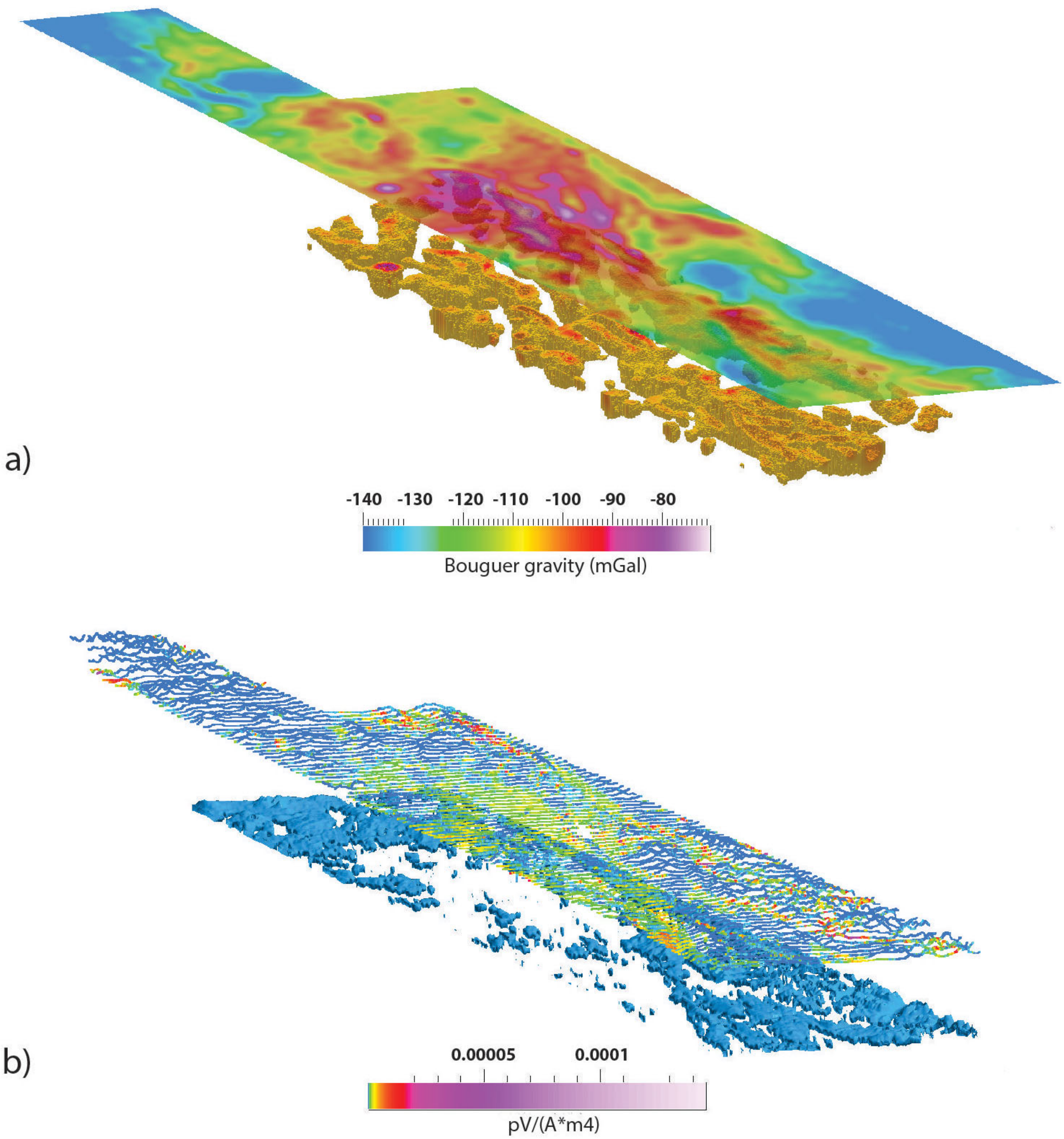

Figure 2. Gravity and electromagnetic (VTEM) data and models focused on for this project: **a)** QUEST Bouguer gravity data and density isosurface at a cut-off of 2.69 g/cm^3 from inversions completed as part of Geoscience BC's 'Identification of New Porphyry Potential Under Cover in British Columbia' Project (Mitchinson et al., 2022). **b)** Electromagnetic (VTEM) data and conductivity isosurface (emphasizing low-conductivity regions) at a cut-off of 0.06 S/m (Siemens/metre) from VTEM inversions completed by Mira Geoscience (Mira Geoscience Ltd., 2009). Abbreviations: A, Ampere(s); m, metre(s); mGal, milligal(s); ms, millisecond(s); pV, picovolt(s).

model trends, and geophysical domains based on these models will be used to update geological interpretations and/or add geophysically derived geological detail through the areas of thickest glacial cover in the central Quesnel terrane.

Preliminary Observations and Interpretations

Trends in VTEM Data and Models

Electromagnetic inversion models prove to be an excellent source of geological information. This is clear when VTEM inversion models are compared to geological maps from the BCGS (Figure 3). Some of the key geological features identified in VTEM inversion models are demonstrated in a series of sections in Figure 4.

Figure 4a shows stitched 1-D VTEM inversion models from the northern end of the QUEST Project area. At the western end of these sections, resistive regions characterize intrusive rocks of the Early Jurassic to Cretaceous Hogem Plutonic Suite, as well as a Cretaceous granodiorite (Jean Marie stock). Takla Group volcanic sedimentary rocks are variable in their conductivity, likely indicating a mix of porous and more massive volcanic stratigraphy. High resistivities characterize mapped augite-bearing basalts. Volcanic agglomerates of the Chuchi Lake succession are mostly conductive, and adjacent Nechako Plateau sedimentary rocks are strongly conductive. The eastern ends of these sections pass through geology near the Mount Milligan deposit. The large pluton north of the Mount Milligan mine is resistive.

Figure 4b shows several sections crosscutting geology at the approximate latitude of the Mount Polley mine. In the west, Chilcotin Group volcanic rocks are strongly conductive. These are known to commonly be highly vesicular (Bevier, 1983), and resulting high porosities would likely enhance conductivity. The Granite Mountain Batholith and adjacent tonalitic intrusive rocks are highly resistive. Cache Creek Complex sedimentary and volcanic rocks are variably conductive, with apparent alternating resistive and conductive stratigraphy. As in the northern sections, Triassic pyroxene basalt is resistive. At the eastern end of the sections, syenitic to monzodioritic rocks hosting the Mount Polley deposit are resistive.

Gravity and Magnetic Data Trends

The VTEM data and models appear to show close spatial correlation with gravity data (Figure 5). This correlation is seen in physical-property data trends and could be, in part, related to rock porosity (Mitchinson et al., 2021). Increased porosity reduces rock mass overall, lowering density relative to an equivalent nonporous rock. Resistivity also decreases with increased porosity. Some of the major trends in gravity and VTEM models are identified in Figure 5. An interesting trend is the spatially correlated resistivity highs and density highs that trend north to northwest through the centre of the project area ('A' labels in Figure 5). Similar correlations are found where pyroxene-bearing basaltic rocks have been mapped in the Mount Milligan and Mount Polley areas.

Massive intrusive bodies that are more felsic in nature, such as felsic intrusions, or metamorphosed felsic or sedimentary domains often exhibit high resistivities correlated with gravity lows ('B' labels in Figure 5). In these cases, the high resistivities suggest low porosities, with apparent low densities attributed to the bulk composition of the rocks, which is dominated by low-density felsic minerals such as quartz, feldspar and albite.

The third major trend between density and resistivity is correlated resistivity lows and gravity lows that are characteristic of more porous sedimentary and volcaniclastic rocks ('C' labels in Figure 5).

Magnetic response, in general, is subdued through the central Quesnel terrane. Three primary sources of magnetic anomalies are indicated in Figure 6. Magnetic volcanic stratigraphy ('a' labels in Figure 6) is found in the southern part of the project area, with more voluminous magnetite-bearing units surrounding Mount Polley. This magnetic volcanic stratigraphy extends southward into the southern Quesnel terrane, where it seems to continue along the western edge of the terrane, possibly beneath recent volcanic deposits (Thomas et al., 2011).

Magnetic highs extending through the central part of the project area are mostly related to discrete, magnetite-bearing, intermediate to ultramafic intrusive bodies ('b' labels in Figure 6; Mitchinson et al., 2022) and recent Chilcotin Group basalt deposits ('c' labels in Figure 6).

The Hogem Plutonic Suite in the northern part of the project area is largely magnetic, and the Early Jurassic phases of this suite define an anomalous trend extending south and then southeast toward the large magnetic intrusion north of the Mount Milligan deposit.

Conclusions

Summary of Geophysical Trends in the Central Quesnel Terrane

From preliminary investigations, QUEST VTEM data and models spatially correlate strongly with gravity data and models from the central Quesnel terrane, distinguishing massive volcanic and intrusive domains from more permeable and porous sedimentary-rock–dominated domains. Magnetic response is weak throughout much of the central Quesnel terrane, with the exception of magnetite-bearing intrusive bodies and occurrences of recent Chilcotin Group basalt deposits. The paucity of magnetic volcanic stratigra-

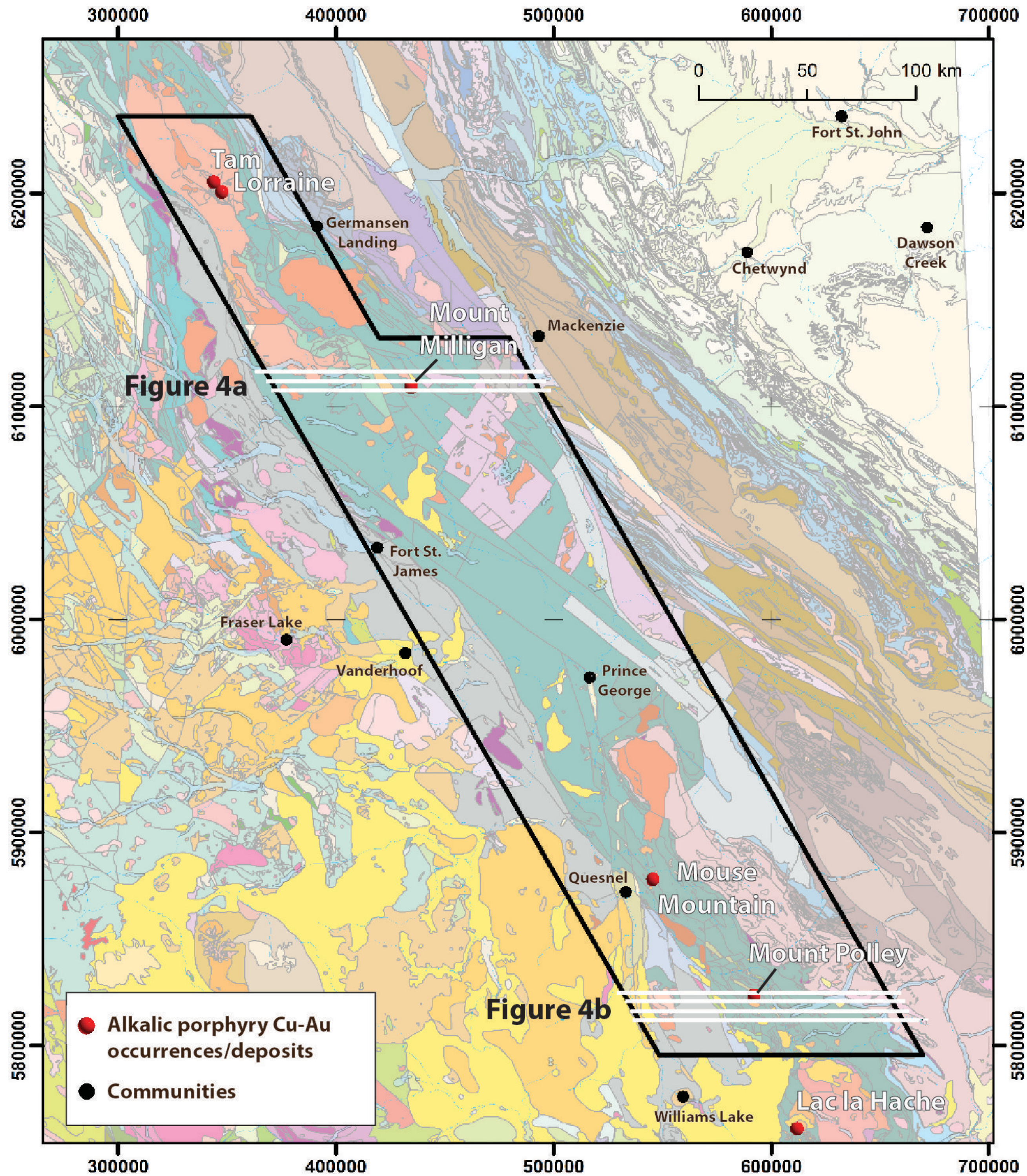

Figure 3. White traces indicate the locations of VTEM inversion models shown in Figure 4. Details are examined from two areas, one in the northern part of the project area near the Mount Milligan deposit and the other in the southern part of the area near the Mount Polley deposit. Project area outlined in black. Geology from BCGS (Cui et al., 2017). Map co-ordinates in UTM Zone 10, NAD 83.

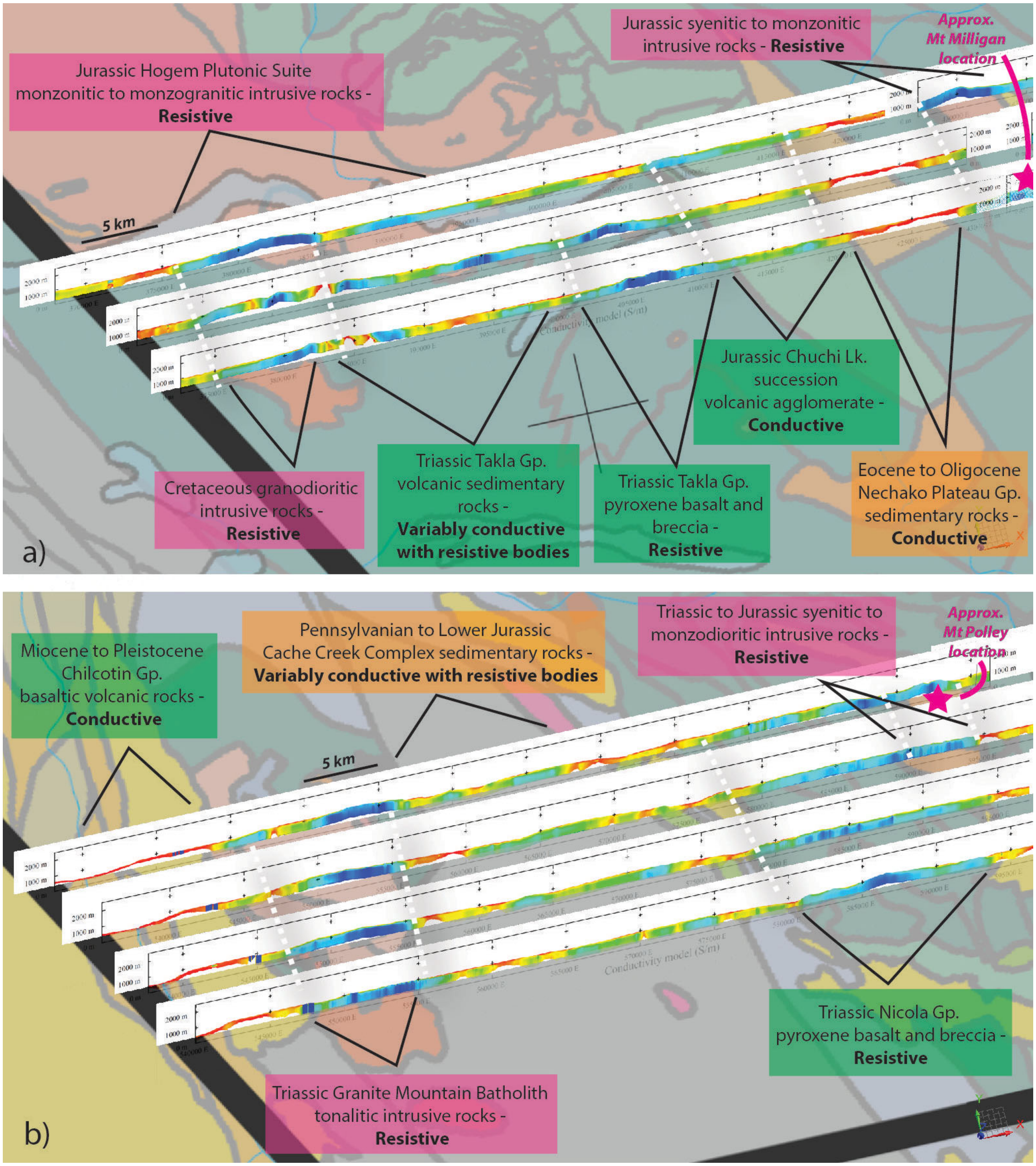

Figure 4. VTEM inversion models from Mira Geoscience (Mira Geoscience Ltd., 2009) superimposed on the BCGS bedrock geology map of BC (Cui et al., 2017): **a)** northern project area sections from Figure 3; **b)** southern project area sections from Figure 3. Inversion models show conductivity data, with red representing high-conductivity (low-resistivity) regions and blue representing low-conductivity (high-resistivity) regions. Pink text boxes highlight electromagnetic characteristics of intrusive rock units, green boxes highlight characteristics of volcanic rock units, and orange boxes highlight characteristics of sedimentary rock units.

phy through the central Quesnel terrane suggests the presence of volcanic assemblages, or volcanic deposits, that differ from the more strongly magnetic stratigraphy found surrounding, and south of, the Mount Polley mine.

Future Work and Deliverables

Available geological maps and geophysical data and models will continue to be explored to further advance hypotheses and data-relationship trends developed to this point. In addition to visual assessment and interpretations of geophysical trends, relationships between data and models will be investigated more quantitatively through application of data querying and cluster analysis of inversion models.

The key project outputs will be 2-D maps with overlain geophysical interpretations summarizing new insights gained through this integrated data analysis.

The project will be concluded in mid-2023, and project deliverables will include

- shapefiles and DXF files of interpreted geological features,
- geology map(s) with newly interpreted features,

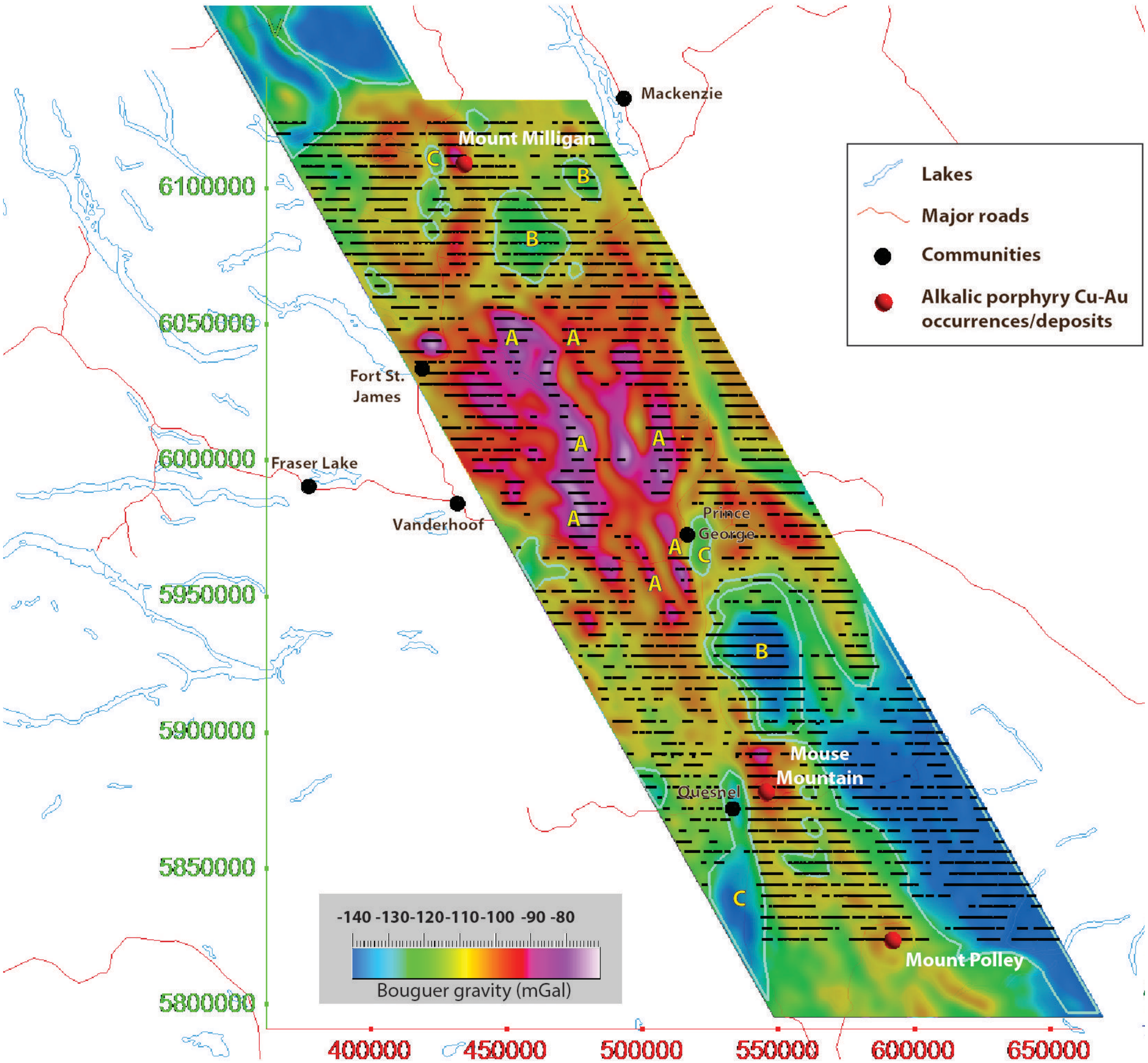

Figure 5. Correlations between resistivity domains from VTEM inversion models and gravity data. Background map is Bouguer gravity and black east-west lines indicate resistive regions along VTEM inversion sections. 'A' labels indicate regions where resistivity highs and gravity highs are co-located and are likely to represent massive, dense, volcanic deposits (low porosities and permeabilities) or ultramafic intrusive rocks. 'B' labels tag regions where resistivity highs correlate with gravity lows and represent massive felsic intrusive or massive metamorphosed bodies. 'C' labels indicate areas where resistivity lows correlate with density lows in porous sedimentary rock units. Map co-ordinates in UTM Zone 10, NAD 83. Abbreviation: mGal, milligal(s).

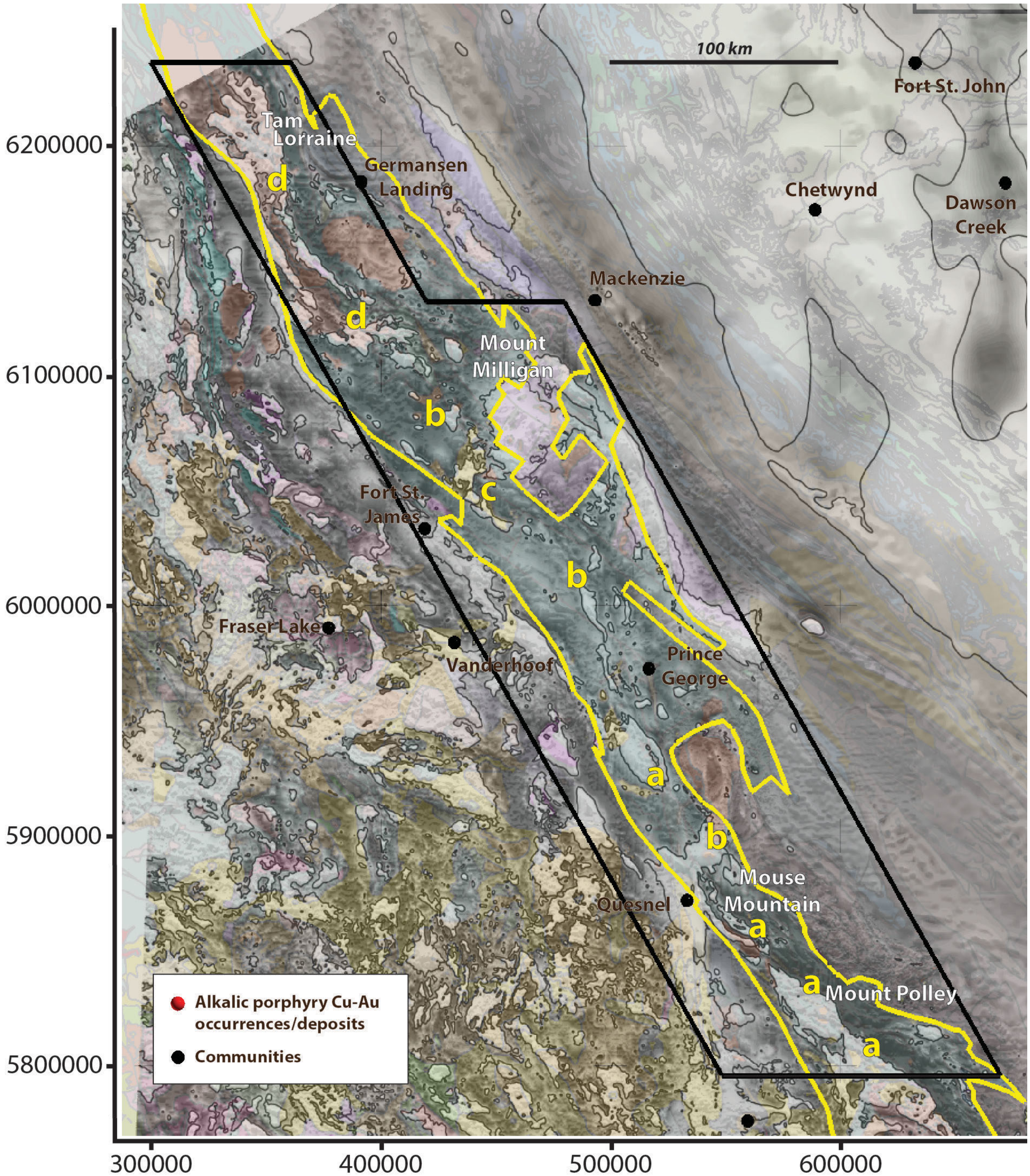

Figure 6. Natural Resources Canada magnetic data (Natural Resources Canada, 2020) in greyscale over the project area, with a contour at 0 nT (white regions are >0 nT). The figure highlights the primary magnetic features seen in the project area. The project area is outlined in black. The Quesnel terrane is outlined in yellow (Colpron and Nelson, 2011), with 'a' labels indicating magnetic volcanic stratigraphy, 'b' labels identifying several areas where magnetic anomalies are associated with discrete mapped and inferred intrusive bodies, 'c' labels indicating magnetic Chilcotin Group basalts, and 'd' labels corresponding to magnetic Hogem Plutonic Suite intrusive rocks.

- map package for ArcGIS and/or Geoscience Analyst, and
- report.

Interpretations from these largely underused geophysical datasets will provide new insights into the beneath-cover geology of the central Quesnel terrane that will be used to help understand how geology there relates to the northern and southern Quesnel terranes, and to identify potential mineral deposit environments and new exploration targets.

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