Mineral Deposit Research Unit

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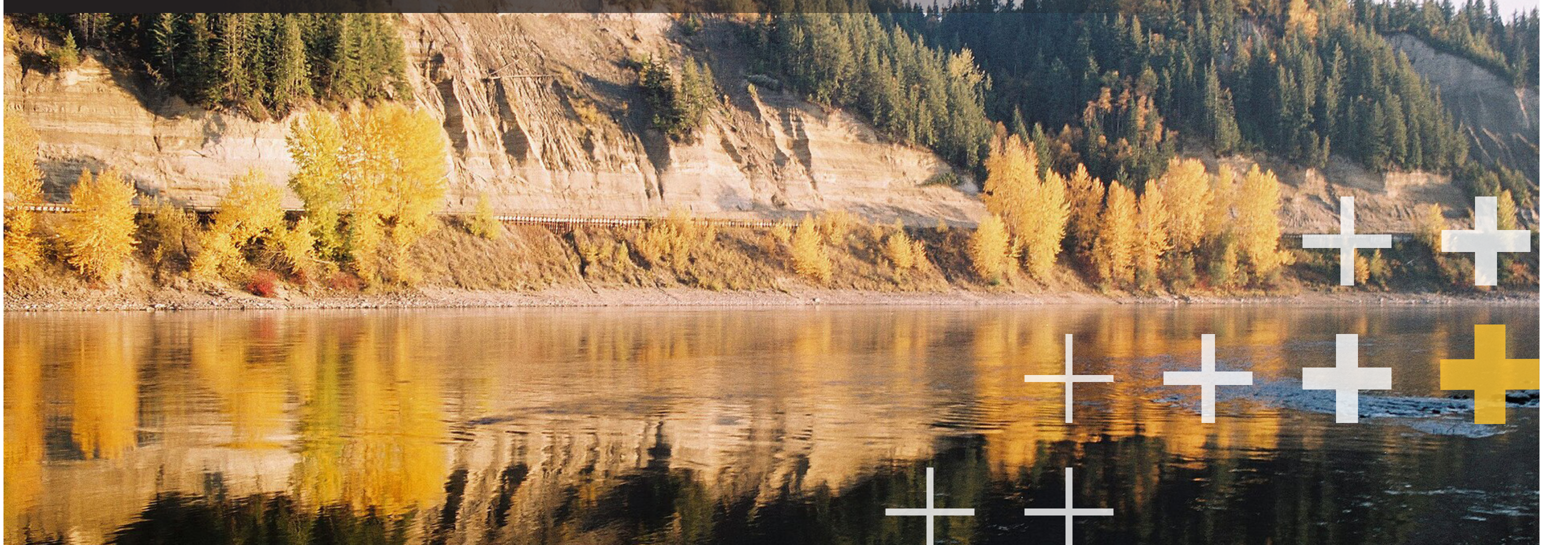

Geoscience BC

REPORT

INTERPRETED UNDERCOVER AND DEEP GEOLOGY OF THE CENTRAL QUESNEL TERRANE, BRITISH COLUMBIA, FROM ELECTROMAGNETIC AND GRAVITY DATA

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[b] MDRU is an industry-supported research unit hosted by the Department of Earth, Ocean and Atmospheric Sciences at The University of British Columbia (UBC). MDRU was formed to provide training, and drive research innovation, in mineral exploration and mining.

Report layout by S. Jenkins

1. Abstract

British Columbia is known globally for its copper and gold-rich porphyry deposits. Many of these deposits are hosted within the Quesnel terrane of British Columbia's Intermontane belt. A large expanse of this prospective terrane is covered by glacial till and other recent sedimentary deposits, deterring mineral explorers who require more geological context when making exploration decisions. Gravity and electromagnetic data were collected as part of Geoscience BC's QUEST program in 2007 to provide new data for interpretation of undercover and deep geology of the Quesnel terrane. Limited interpretation has been done using these datasets, with most past geophysical interpretations focusing on magnetic data. Both gravity and electromagnetic data track variations in volcanic stratigraphy under cover, enabling linkages to be made between geology mapped in the northern and southern Quesnel terrane. These geophysical datasets delineate a western domain of high density, high resistivity rock consistent with more massive volcanic stratigraphy, and an eastern domain of low density, low resistivity material likely of sedimentary origin. Isolated high density and high resistivity bodies located throughout this stratigraphy have geophysical characteristics similar to known Quesnel terrane porphyry deposit host intrusions. Gravity and electromagnetic data interpretations add baseline knowledge to support an evolving understanding of the magmatic and tectonic history of the Quesnel terrane, and develop further insight into obscured and deep bedrock geology to provide context for mineral exploration.

2. Introduction

The Quesnel terrane of British Columbia is largely composed of a Late Triassic–Early Jurassic volcano-magmatic arc that amalgamated onto the western edge of the North American Craton. This geologic terrane is known worldwide for its rich porphyry copper and gold deposits. Six are being mined currently: Copper Mountain, Highland Valley, New Afton, Mount Polley, Mount Milligan, and Gibraltar. Highland Valley is Canada's largest copper mine and produced roughly 20% of Canada's copper in 2022 (Natural Resources Canada, 2024). Mineral explorers continue to be interested in this terrane, with its significant porphyry prospectivity, as well as its existing infrastructure and geographic access. Mineral exploration has been mostly focused in the northern and southern parts of the terrane where younger sedimentary deposits overlying prospective bedrock are thinner and it is easier to map and sample bedrock directly. Significantly less exploration has been carried out in the central parts of the Quesnel terrane where over 400 m of glacial till and other sedimentary deposits (Mitchinson et al., 2022) can overlie bedrock (Figure 1). Based on limited mapping, geologic units in the central Quesnel terrane are inferred to be similar to geologic units hosting mineralization to the north and south, and mineral potential should remain high. To enhance knowledge of bedrock and deep geology of the covered regions of the central Quesnel terrane, and assess potential for mineral-forming environments, two regional geophysical surveys were commissioned by Geoscience BC as part of their 2007 QUEST program (Barnett and Kowalzcyk, 2008). These Versatile Time-Domain Electromagnetic (VTEM™) and gravity surveys reveal information about the density and resistivity of the bedrock and sedimentary cover which can be linked to rock type, rock texture, and structure. This study generates new interpretations of geology under cover in the central Quesnel terrane. These interpretations provide a link between volcanic stratigraphy mapped in areas of greater bedrock exposure in the northern and southern Quesnel terrane, identify discrete bodies that may represent prospective intrusive rocks under cover, and reveal zones of structural disruption.

3. Background

3.1. Quesnel terrane geology, sedimentary cover, and mineral deposits

The Quesnel terrane is part of the Intermontane belt of British Columbia, which also includes the Cache Creek and Stikine terranes to its west. These represent allochthonous arc terranes that were amalgamated onto the western

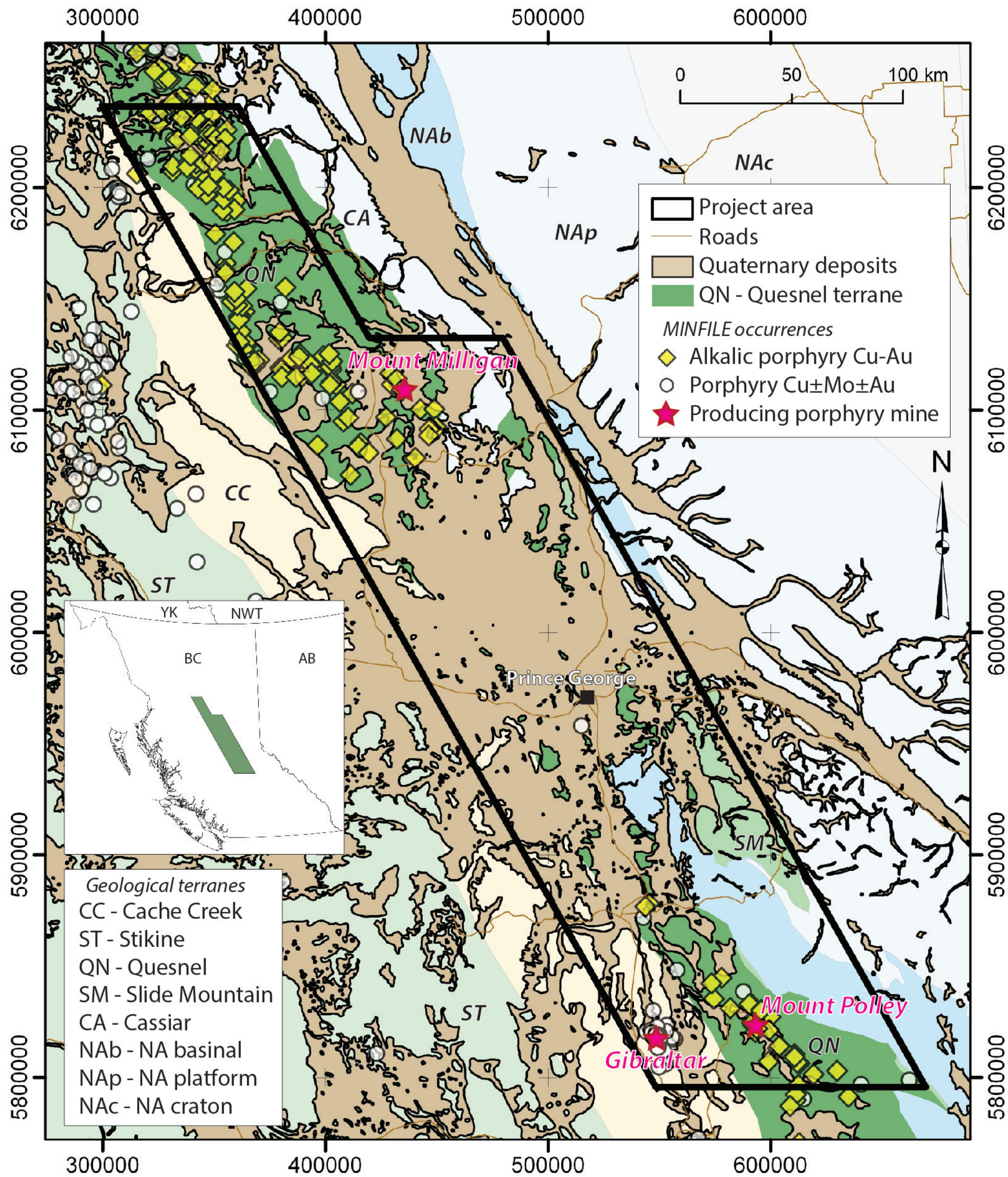

Figure 1: The study area for this project corresponds to Geoscience BC's QUEST Project study area (green polygon in inset map). The light-brown region shows the distribution of Quaternary deposits mapped by the BC Geological Survey (Cui et al., 2017). Significant porphyry copper±gold±molybdenum and porphyry copper-gold mineral occurrences are known in the northern and southern extents of the project area. Mount Milligan, Mount Polley and Gibraltar are porphyry deposits currently in production within 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 displayed 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.

edge of the North American Craton. The north–northwest-striking Quesnel terrane forms a narrow belt extending from the northern US border to the northern border of British Columbia and comprises rocks that represent a volcano-magmatic arc that formed between the Late Paleozoic and the Mesozoic (Nelson and Colpron, 2007). Volcanic and volcano-sedimentary rocks make up much of the bedrock geology of the Quesnel terrane (Cui et al., 2017). Felsic to intermediate intrusive bodies, dominantly of Triassic, Jurassic, and Cretaceous age, are exposed all along its length. More recent Eocene to Pleistocene volcanic activity deposited sub-horizontal volcanic deposits, primarily andesitic to basaltic volcanic flows (flood basalts), that overlie Mesozoic geology in parts of the belt (e.g., Chilcotin

Group rocks; Mathews, 1989). Quaternary age sedimentary cover, dominated by glacial tills, blankets bedrock in low-lying areas of the Quesnel terrane, with an especially large volume of material accumulated in south-central Quesnel terrane, centered around the city of Prince George.

The Quesnel terrane hosts a significant number of porphyry deposits and occurrences. It is one of few type localities for alkalic porphyry copper-gold deposits (Jensen and Barton, 2000). These gold and platinum group element-enriched porphyry deposits differ from calc-alkalic type porphyry deposits in several ways, with key differences being composition of magmatic host rock, alteration mineral products, metal constituents, and size (Chamberlain et al., 2007; Hanley et al., 2020). They are found in limited locations around the globe, with closest analogues being deposits in the Macquarie Arc, New South Wales, Australia (Cooke et al., 2007).

Hundreds of porphyry mineral occurrences are recorded to occur in the Quesnel terrane (MINFILE, BC Geological Survey, 2020). There is a sudden and significant paucity of these occurrences where sedimentary cover thickens in the central Quesnel terrane. Sedimentary cover has been a deterrent to exploration, making it difficult to directly sample and map rocks, and therefore, to understand the geologic setting or extrapolate structural and geological trends relevant to mineralization from more well-mapped areas. In addition, overburden would be a cost consideration for diamond drilling and mining. Nonetheless, the mapped (where exposed) and inferred continuation of Triassic-Jurassic volcanic arc rocks from southern to northern Quesnel terrane would suggest that porphyry deposit prospectivity continues to be high through the covered areas. With limited outcrop to provide direct observation of geology, remote mineral detection techniques like surficial geochemical methods and geophysical methods are heavily relied on to direct mineral exploration.

3.2. Previous geophysical interpretations in the central Quesnel terrane

Geoscience BC's 2007 QUEST geophysical surveys (Figure 2) provided the geoscience and mineral exploration industries excellent new regional data that stimulated mineral exploration and discovery in the central Quesnel terrane. The QUEST electromagnetic (VTEM) survey (Geotech Limited, 2008) provided a new type of data with which to evaluate and model the conductivity of the sedimentary cover and bedrock of the Quesnel terrane. The QUEST gravity survey (Sander Geophysics Limited, 2008) represented a significant upgrade in resolution of this type of data in central British Columbia; new gravity data was collected at a 2 km line spacing, improving on existing national gravity data collected at approximately 10 km spacing.

These datasets, along with magnetic data collected as part of the QUEST VTEM survey, and magnetic data available from Natural Resources Canada (Natural Resources Canada, 2020), have been the focus of several past interpretation and modelling studies:

- Mira Geoscience (Mira Geoscience Limited, 2009) modelled the QUEST gravity and VTEM data using geophysical inversion techniques. This resulted in 3D density models and 1D conductivity models stitched to create 2D conductivity sections for each line of the VTEM survey;
- Sánchez et al. (2015) completed a structural and geological domain interpretation for the survey area using magnetic and gravity data;
- Most recently, Mitchinson et al. (2022) completed a study that developed 3D models of sedimentary cover thickness and identified regional porphyry targets based on electromagnetic, magnetic, and gravity data within the QUEST project area.

Processed magnetic and gravity data appear to be largely unaffected by sedimentary cover rocks in the Quesnel terrane and respond mainly to underlying bedrock magnetic susceptibility and density contrasts, making them useful datasets for interpreting bedrock geology. Electromagnetic data can detect both cover sequences and variations in underlying bedrock geology (Kowalczyk et al., 2010).

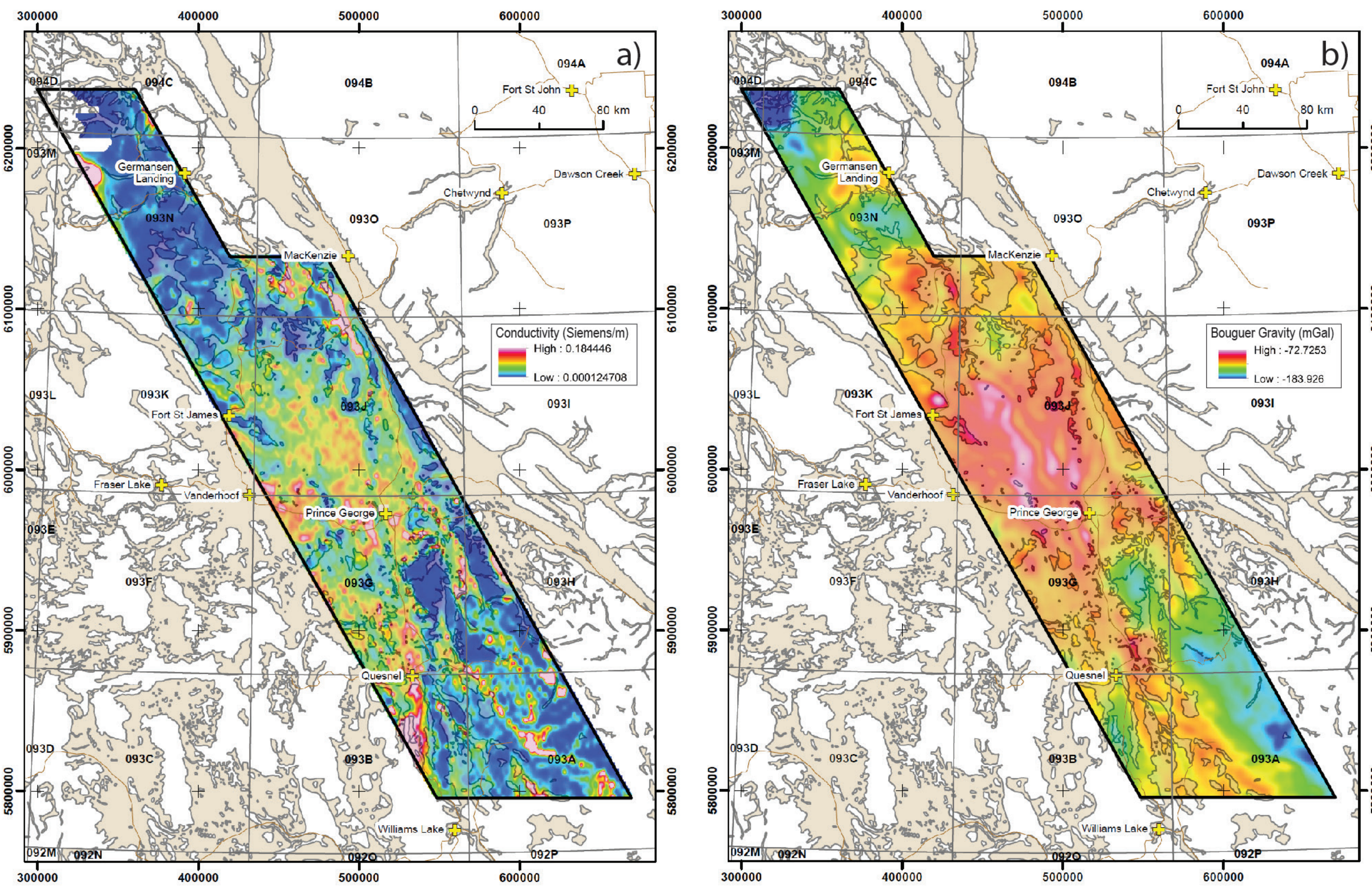

Figure 2: Geoscience BC QUEST project data used for geological interpretations in this project: a) Conductivity model from VTEM data (Mira Geoscience Limited, 2009), b) Bouguer gravity data. Light-brown regions are areas of Quaternary cover deposits (Cui et al., 2017). Map co-ordinates in UTM Zone 10, NAD 83.

4. Data used in this study

4.1. Geological data

Existing geological maps and previous interpretational work were sourced to help identify causes of geophysical responses, and to guide new interpretations. The British Columbia Geological Survey (BCGS) bedrock geology database (Cui et al., 2017) represents the most recent compilation of geological mapping from British Columbia. This map database compiles and captures information from bedrock geology maps for specific geographic regions or NTS map sheets, and is periodically updated to incorporate new data. The bedrock geology of the Quesnel terrane has been mapped by geologists from the Geological Survey of Canada and the BCGS. Recent mapping within and overlapping with the project area that directly influenced interpretations herein, include that documented in Schiarizza (2019) and Logan et al. (2020). Schiarizza's (2019) mapping focuses on the Bridge Lake-Quesnel River area, just south of the main project area, and Logan et al. (2020) summarize geology and mineral deposits in the Hogem batholith area, which overlaps the northern part of the main project area. Volcanic and sedimentary rock facies relationships from these recently updated maps are used to build an understanding of the depositional history and evolution of the Triassic-Jurassic volcanic arc that dominates the Quesnel terrane.

Additional maps and reports sourced to aid interpretations included Tipper (1961), Struik et al. (1990), Struik (1994), Panteleyev et al. (1996), Hastings et al. (1999), and Schiarizza et al. (2013). These historic to more recent maps and associated reports were referred to during this work to identify, validate, trace, and interpret geophysical trends in relation to geological features.

4.2. Geophysical data

The QUEST electromagnetic and gravity surveys were completed in 2007. The electromagnetic survey was an airborne Versatile Time-Domain Electromagnetic (VTEM™) survey run by Geotech Limited (Geotech Limited, 2008) that collected both electromagnetic and magnetic data. The survey was flown east-west, and 111 lines of data were collected at a line spacing of 4 km. The QUEST airborne gravity survey was completed by Sander Geophysics (Sander Geophysics Limited, 2008), with data collection along east-west lines at a line spacing of 2 km.

Interpolated 1D VTEM inversion models from Mira Geoscience (Mira Geoscience Limited, 2009) were used to interpret zones of resistive versus conductive geology underlying sedimentary cover along-line. Information along-line is high resolution (1 data point every 2–3 m). A 4-km distance between adjacent VTEM lines means features smaller than 4 km situated between lines may not be captured in the data, thus interpolation in the north-south direction would be poorly supported. Because of this, interpretations were restricted to the pseudo-2D east-west conductivity models. As part of VTEM inversion modelling Mira Geoscience completed depth of investigation analyses which estimates the depths to which the survey is sensitive. Details on the methodology are found in Mira Geoscience's report on the modelling. Generally, sensitivity was determined to be <1 km, but this is highly dependent on whether conductive surficial sediments are present, which can hinder detection of underlying rocks.

Bouguer gravity grids were used for 2D gravity data interpretations. Gravity grids have 250 m × 250 m cells. Gravity data at this resolution allow for interpretation of major density contrasts within the crust. Strong gravity highs influenced by deep, dense crustal features can obscure higher frequency, near-surface anomalies. As such, the first vertical derivative (1VD) of gravity was used to emphasize near-surface features in gravity data more aligned with the scale of VTEM sensitivities.

Although VTEM and gravity data are the focus of this work, magnetic data helped to validate some interpretations from these geophysical datasets. Magnetic data used for this purpose are total magnetic intensity (TMI) data from Natural Resources Canada (Natural Resources Canada, 2020) gridded at 200 m.

4.3. Physical property data

The Canadian Rock Physical Property Database contains data from rock samples collected across Canada (Enkin, 2018). Physical property data from the Quesnel terrane were extracted, and these data were used to guide geophysical interpretations.

5. Regional petrophysical and geophysical correlations with Quesnel terrane geology

5.1. Physical property trends in the QUEST project area

Geophysical responses recorded by potential fields and electromagnetic surveys are controlled by the physical properties of the rocks in the Earth's crust. Magnetic responses are a function of the magnetic susceptibility of geological bodies or material in the subsurface, and gravity responses relate to density contrasts within the Earth. Electrical surveys respond to the electrical conductivity or resistivity of a material or pathways within a material. It is important to understand the ranges of physical properties of rocks expected to occur in a survey area prior to making any assumptions or interpretations of geophysical data.

With the focus on gravity and electromagnetic data for this project, density and resistivity data collected from a variety of Quesnel terrane lithologic units were assessed. Gabbroic rocks and ultramafic rocks are the highest density rocks in the Quesnel terrane physical property data subset (Table 1), with medians of 2.95 g/cm³ and 3.0 g/cm³, respectively. Andesitic rocks have a median density of 2.75 g/cm³, and basaltic rocks, 2.84 g/cm³. Mafic and ultramafic rocks are typically dense due to their mineralogy which is dominated by dense iron and magnesium minerals like pyroxene. Mafic rocks in the Quesnel terrane have a large range of resistivities (Table 1, Figure 3), from a low of 15 ohm-m to a high of 154,994 ohm-m. The resistivity of a rock is influenced by the amount and distribution of conductive minerals contained in the rock. Resistivity is also affected significantly by the rock's porosity. Enkin (2018) demonstrates these relationships for samples from the Canadian Rock Physical Property Database, and Mitchinson et al. (2013) showed that porosity plays an important role in controlling rock resistivity in porphyry deposit settings

Table1: Summary of density and resistivity data from major rock types in the Quesnel terrane.

	Density (g/cm³)				Resistivity (Ohm-m)			
Lithology	**Count**	**Med**	**Min**	**Max**	**Count**	**Med**	**Min**	**Max**
Ultramafic rock	27	**3.00**	2.58	3.43	0			
Gabbro	27	**2.95**	2.77	3.23	1	**12663**	12663	12663
Basalt	205	**2.84**	2.24	3.72	64	**4583**	15	154994
Greenschist	1	**2.75**	2.75	2.75	0			
Volcanic rock	4	**2.75**	2.66	2.82	0			
Andesite	29	**2.75**	2.57	2.90	4	**2233**	1589	5166
Diorite	67	**2.86**	2.55	3.37	8	**4629**	694	27818
Monzodiorite	24	**2.80**	2.60	2.97	0			
Granodiorite	27	**2.67**	2.59	3.00	1	**9372**	9372	9372
Monzonite	28	**2.68**	2.55	2.84	19	**10511**	682	67165
Syenite	19	**2.66**	2.48	2.87	1	**1991**	1991	1991
Granite	4	**2.77**	2.65	2.86	0			
Volcanic sediment	184	**2.76**	2.43	3.09	7	**463**	100	3699
Sedimentary rock	123	**2.74**	2.36	3.05	3	**268**	209	387
Limestone	25	**2.71**	2.65	2.84	0			

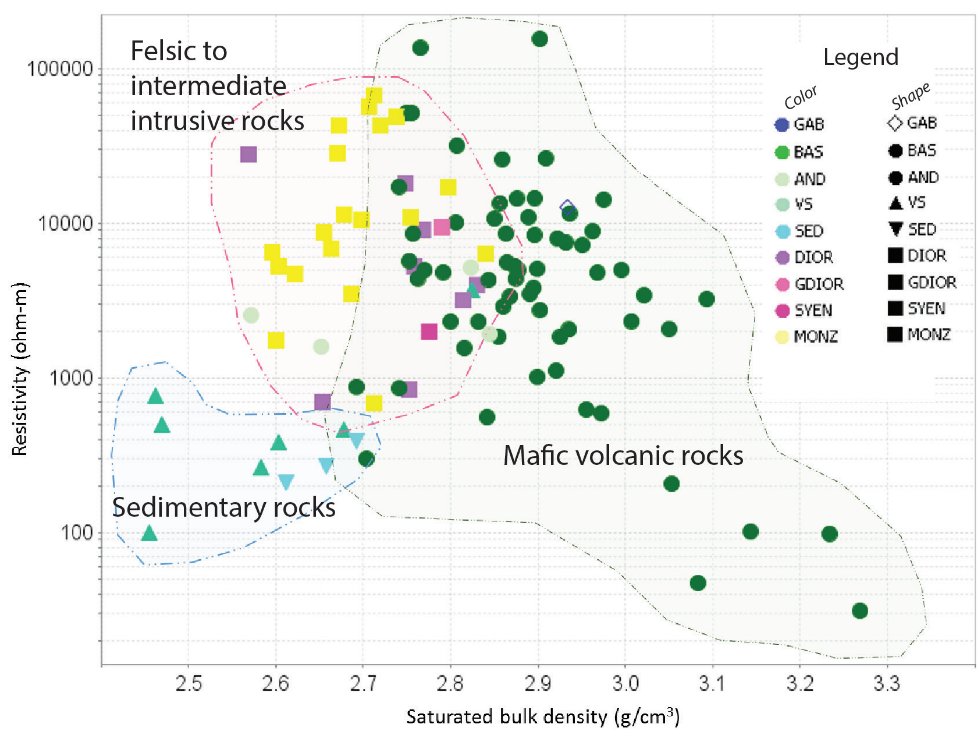

Figure 3: Saturated bulk density versus resistivity plot with Quesnel terrane sample measurements extracted from the Canadian Rock Physical Property Database (Enkin, 2018). Abbreviations: AND, andesite; BAS, basalt; DIOR, diorite; GAB, gabbro; GDIOR, granodiorite; MONZ, monzonite; SED, sedimentary rocks; SYEN, syenite; VS, volcanic sedimentary rocks.

when there are not abundant conductive minerals (sulfides). The trends in resistivity for mafic rocks in the Quesnel terrane are assumed to be primarily due to variations in rock porosity, with lower resistivity (higher conductivity) mafic rock samples having high porosities possibly caused by brecciation or fracturing of the rock, high vesicularity, strong alteration, or weathering. Higher resistivity samples are likely those that are more massive, or coherent in nature, with lower porosities. A small subset of mafic volcanic rocks (Figure 3) are dense (3 to 3.3 g/cm^3) with low resistivities (<300 ohm-m). These are basaltic samples from near the Mount Milligan deposit that contain between 12–38% sulfides+oxides (Mitchinson et al., 2013), which have increased the densities and lowered the resistivities of these samples.

Felsic to intermediate composition intrusive rocks have median density values ranging from 2.66 gcm^3 (syenite) to 2.86 g/cm^3 (diorite), with the upper ranges overlapping with mafic rock densities. Syenite, monzonite, and granodiorite samples have distinctly lower median densities than monzodiorite and diorite samples. This could be due to lower overall abundances of dense mafic (Fe-rich) minerals relative to felsic (Fe-poor minerals) in these rock suites, or to possible secondary alteration of the rocks which can break down primary minerals and/or add lower density alteration minerals. Felsic to intermediate intrusive rocks have resistivities ranging from 682 ohm-m to 67,165 ohm-m, with the higher resistivities inferred to reflect the commonly massive nature of intrusive rocks.

Sedimentary rocks have a large range of densities from 2.36 g/cm^3 to 3.09 g/cm^3. A high diversity of rock textures and compositions are expected within this sample group. Sedimentary rocks have distinctly lower resistivities (100 ohm-m to 3,699 ohm-m) relative to mafic volcanic and felsic to intermediate intrusive rocks, which is interpreted to be a consequence of their higher porosities relative to more massive intrusive and volcanic rocks.

These physical property characteristics indicate that there are broad physical property distinctions between some of the major rock types in the Quesnel terrane. There remains overlap, however, meaning that rocks cannot be uniquely identified from their rock property values or their geophysical responses.

5.2. Electromagnetic trends in the QUEST project area

Electromagnetic (VTEM) data from the QUEST project contain information about the resistivity (or conductivity, the reciprocal of resistivity) of the subsurface. Mitchinson et al. (2022) used VTEM inversion models to interpret depth of surficial sedimentary deposits. Surficial deposits were represented in VTEM inversion models from Mira Geoscience (Mira Geoscience Limited, 2009) by a thin semi-horizontal layer of conductive material. Beneath this cover, variability in the conductivity models reflects geological variability and geologic structure within bedrock.

For this work, manual interpretation of VTEM inversion models focused on delineating resistive zones from low resistivity (conductive) zones within bedrock beneath conductive overburden. Resistive domains below cover were digitized from the 111 east-west inversion models. These interpretations are focused on the top portion only of the resistors, and remain open at depth due to uncertainty with regard to depths of investigation. Based on rock property evaluations and comparisons to geological maps, the interpreted resistors represent intrusive rocks, or other massive or coherent geologic units. Low resistivity domains are expected to represent rock packages dominated by sedimentary rock units. It is important to note that in areas where there are very high conductivity surficial sediments, electromagnetic current may not be capable of penetrating through that conductive substrate to access the underlying rock (Mira Geoscience Limited, 2009). In parts of the central project area where sedimentary cover is particularly conductive or very thick, bedrock resistors cannot be interpreted from VTEM models.

Localized evaluations indicate broad correlations between bedrock units and conductivity/resistivity domains in the subsurface when BCGS bedrock geology and VTEM inversion models are compared. Figure 4 displays four VTEM inversion lines from the southern QUEST project area against the BC bedrock geology map. From west to east several trends are noted:

- Chilcotin Group volcanic rocks are conductive, which is expected due to their high vesicularities (Bevier, 1983) and expected related porosities;
- The Triassic Granite Mountain batholith is resistive, typical of massive intrusive bodies;
- Cache Creek Complex sedimentary rocks are highly variable in terms of their conductivity/resistivity responses, as are other sedimentary domains, possibly reflecting more and less porous stratigraphic sub-units;
- Triassic to Jurassic Nicola Group pyroxene-phyric basaltic units are typically resistive; and
- Triassic to Jurassic syenitic to monzodioritic intrusive rocks hosting the Mount Polley porphyry deposit are resistive.

These trends provide support for interpretations in other parts of the project area.

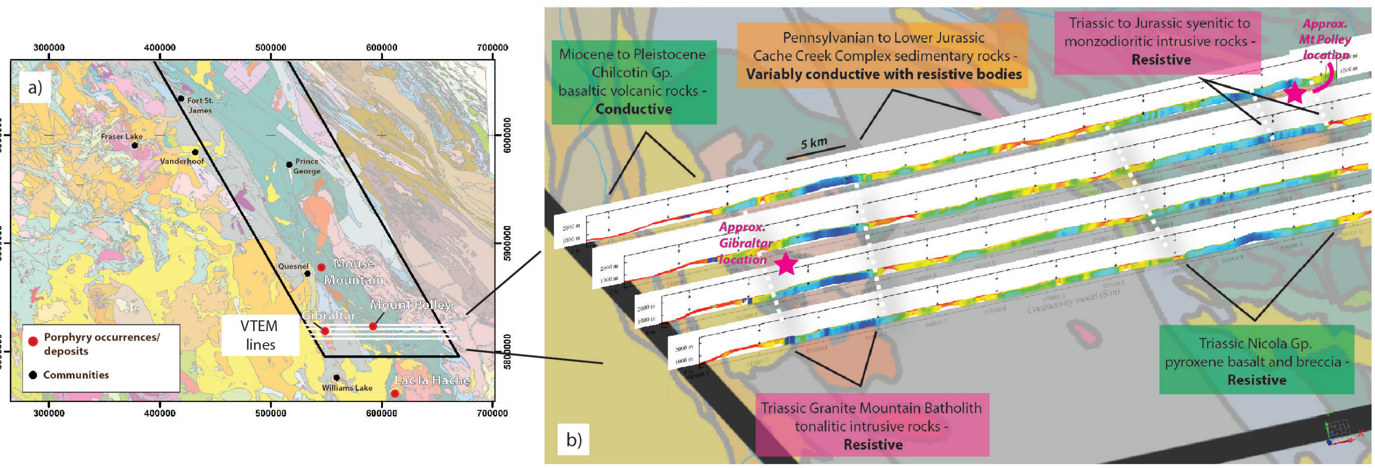

Figure 4: Four VTEM 2D inversion lines from the southern QUEST project area (Mira Geoscience Limited, 2009) intersect volcanic, sedimentary, and intrusive rocks of the Cache Creek and Quesnel terranes: a) Location of four VTEM lines on BCGS bedrock geology map; b) Close-up of four VTEM inversion lines with conductivity displayed. Reds and yellows indicate conductive regions within the subsurface, and blues indicate resistive regions. Trends between conductivity and geology are indicated. Pink text boxes highlight conductivity trends associated with intrusive rocks, green boxes indicate conductivity trends within different types of volcanic rocks, and orange boxes indicate conductivity trends within sedimentary rock domains.

5.3. Gravity trends in the QUEST project area

Bouguer gravity data grids from the QUEST project area were integrated with geological maps and VTEM inversion interpretations, to complete a preliminary assessment of gravity trends in the project area. Variations in gravity data reflect density contrasts in the crust and it is expected that rocks that strongly contrast in density should be differentiable in the gravity data.

Comparing gravity data with VTEM interpretations reveals correlations between these data (Figure 5). Three geological domains can be interpreted that match trends seen in resistivity and density data (Figure 3). Some linear and localized gravity highs correlate with resistors identified from the VTEM inversions (labelled “A” on Figure 5). These correlated gravity-resistivity highs correspond largely to mapped Nicola Group volcanic rocks on the BCGS bedrock geology map, in particular, those documented in bedrock geology database metadata to be pyroxene-phyric. These responses are consistent with physical property data from Quesnel terrane mafic volcanic rocks (Section 5.1).

Other localities show correlations between gravity lows and resistivity highs interpreted from VTEM inversions (labelled “B” on Figure 5). Several of these low gravity-high resistivity regions align with the locations of mapped felsic intrusive rocks that are lower density than surrounding volcanic rocks, and are resistive due to the typically massive, coherent nature of plutonic rocks. A third domain is characterized by gravity lows and resistivity lows (labelled "C" on Figure 5). These domains are often linear and alternate with the linear gravity-resistivity highs. Based on geological information from the southern project area, and on physical property data, these regions most likely represent sedimentary rock deposits, with low densities and low resistivities reflecting higher porosities common to sedimentary rocks, and/or alteration or weathering (due to enhanced porosity).

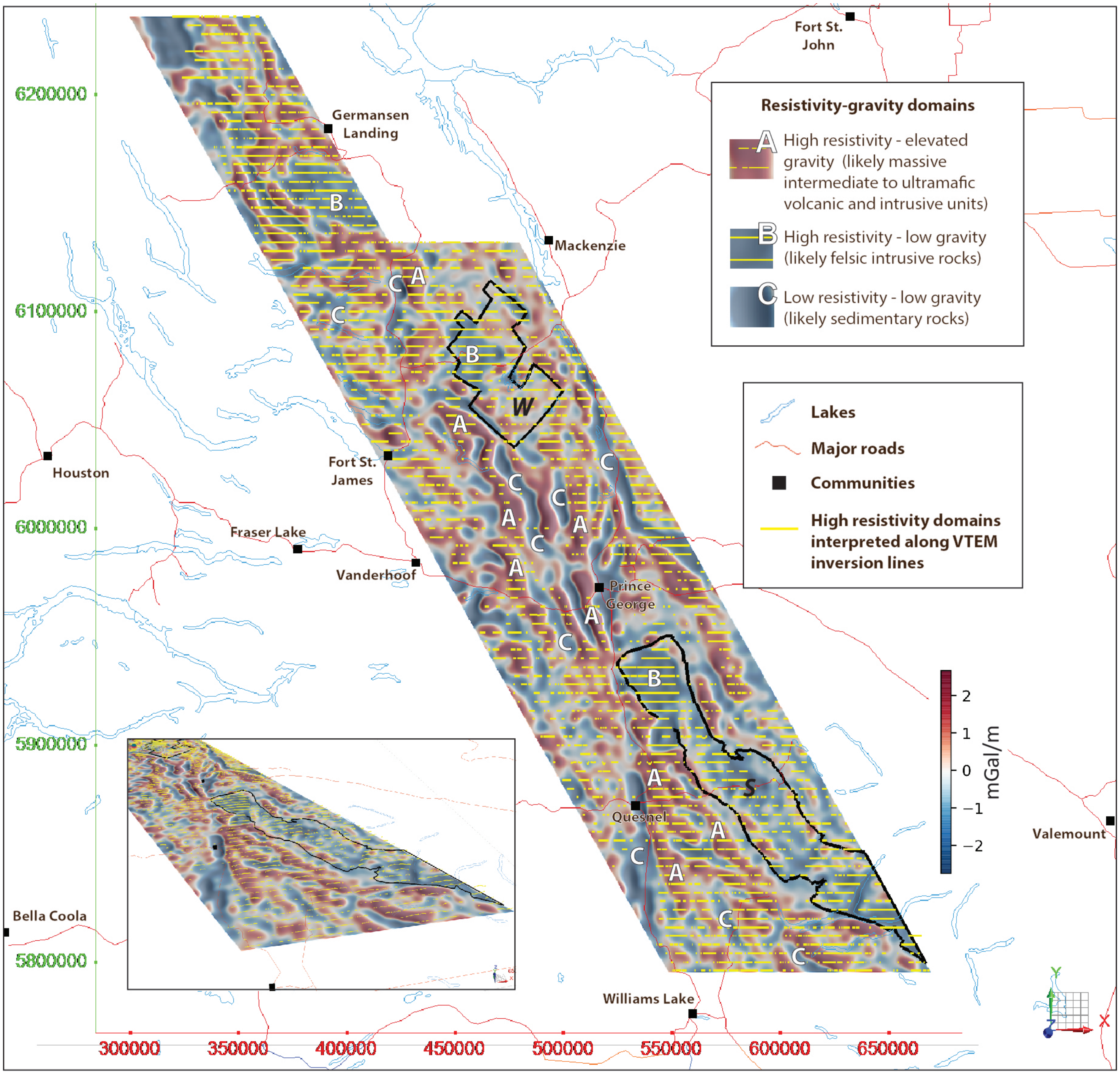

Figure 5: Correlations between resistivity domains from VTEM inversion models and gravity data. Background map is Bouguer gravity and yellow east-west lines indicate resistive regions interpreted below sedimentary cover along VTEM inversion sections. "A" labels indicate regions where resistivity highs and gravity highs are co-located and are likely to represent massive, dense, volcanic deposits or intermediate to ultramafic composition intrusive rocks (low porosities and permeabilities). "B" labels tag regions where resistivity highs correlate with gravity lows and represent massive felsic intrusive or massive metamorphosed bodies of felsic composition. "C" labels indicate areas where resistivity lows correlate with density lows in porous sedimentary rock units. Inset map shows 3D perspective view of interpreted high resistivity domains overlain on the Bouguer gravity grid. Map co-ordinates in UTM Zone 10, NAD 83. Abbreviation: mGal, milligal(s).

5.4. Magnetic trends in the QUEST project area

Some broad observations are made here in terms of magnetic trends in the Quesnel terrane, which serve to support regional interpretations. Magnetic volcanic stratigraphy (labelled “a” in Figure 6) occurs south of Prince George, within the area of the Mouse Mountain porphyry occurrence, around the Mount Polley deposit, and extending southward where it may occur under Chilcotin Group basaltic rocks (Thomas et al., 2011). South of this, southern Quesnel terrane mafic volcanic rocks are largely non-magnetic (Figure 7).

The volcanic rocks making up the central part of the Quesnel terrane (from just south of Prince George to the northern margin of the QUEST project area) are magnetically subdued (Figure 6). The magnetic lows of the central project

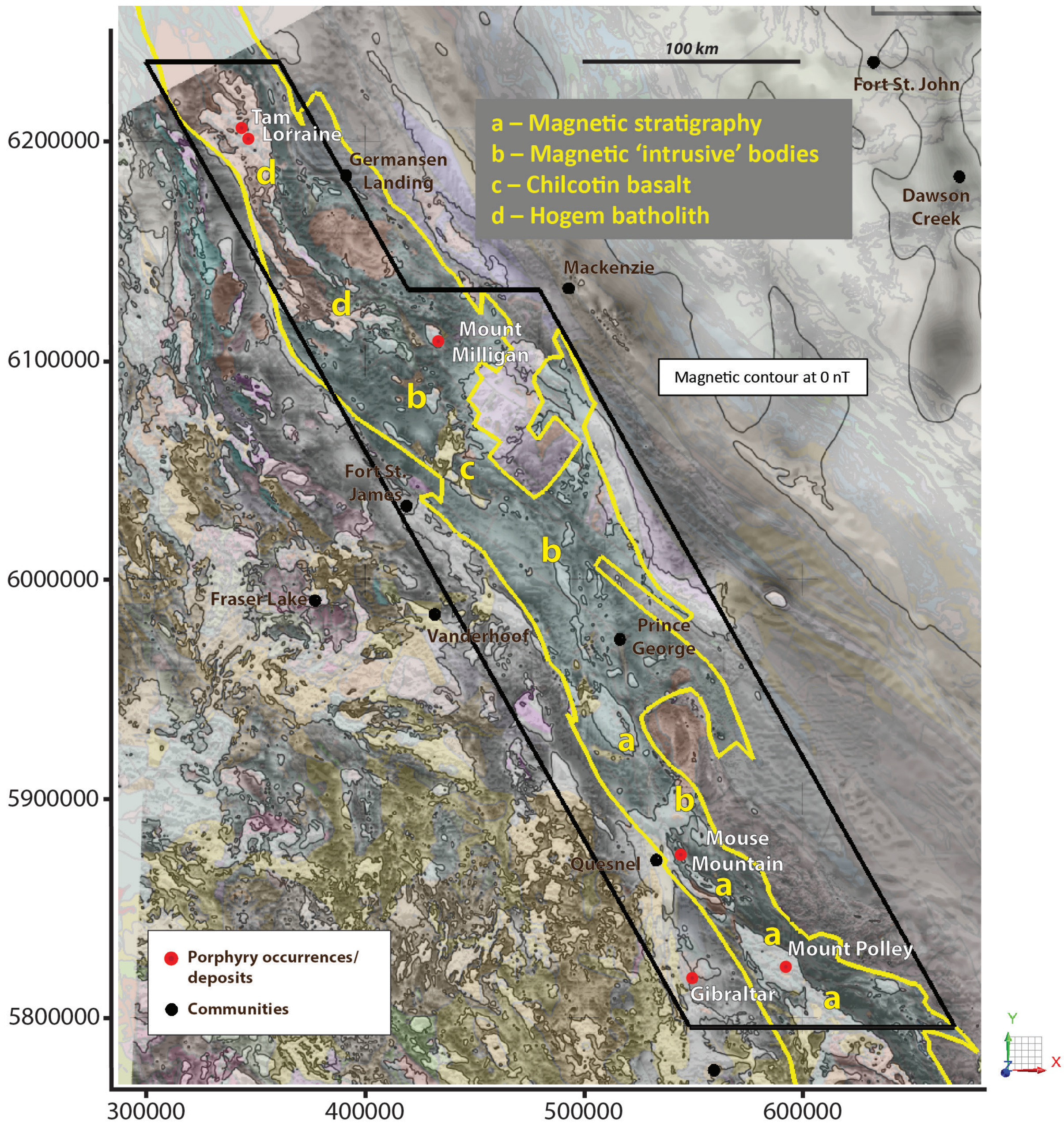

Figure 6: Natural Resources Canada magnetic data (Natural Resources Canada, 2020) in greyscale over the project area, with a contour at 0 nanoteslas (white regions are >0 nT). The figure highlights the primary magnetic features seen in the project area. The project area is outlined in black. The Quesnel 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 basaltic rocks, and “d” labels corresponding to magnetic phases of the Hogem Plutonic Suite. Map co-ordinates in UTM Zone 10, NAD 83.

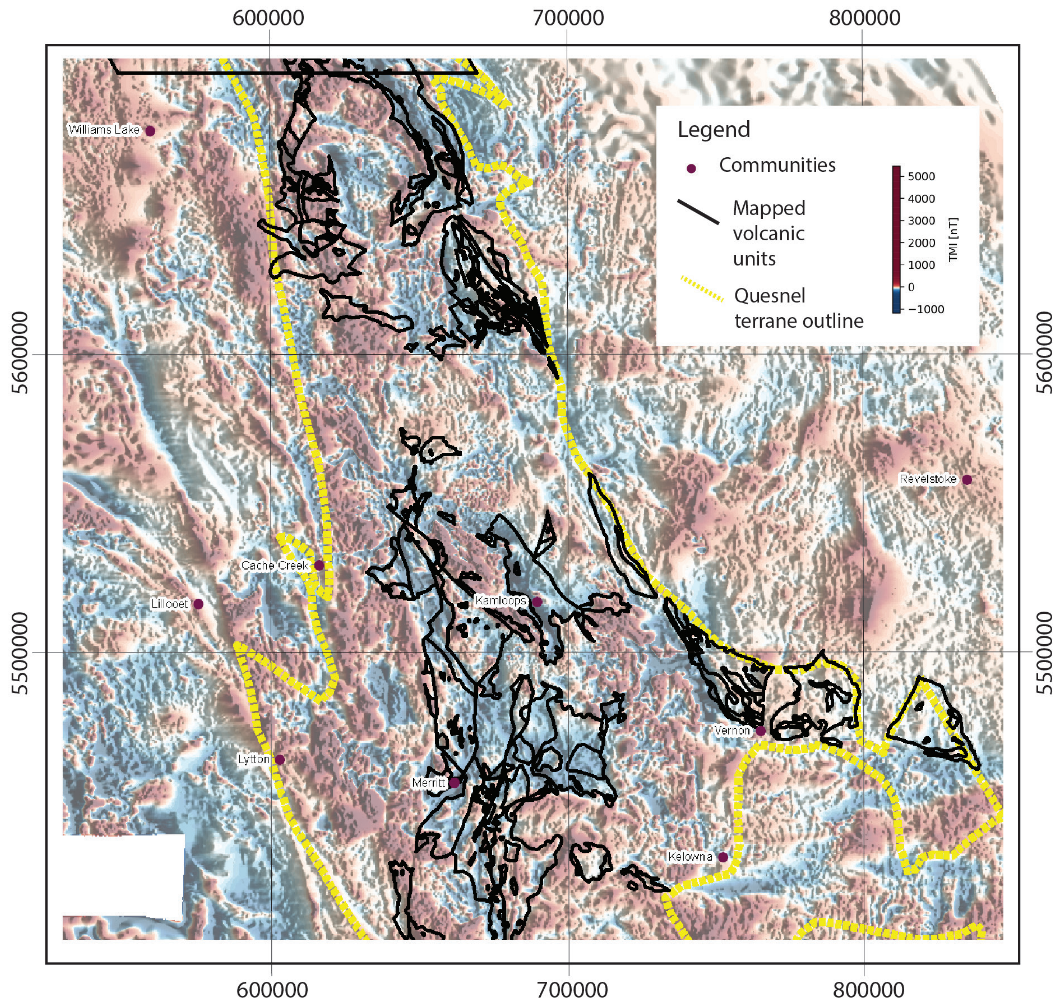

Figure 7: . Total magnetic intensity map from the southern Quesnel terrane. High magnetism is represented by red colors, and low magnetism represented by blue colors. Mafic volcanic Nicola Group units (black outlines) are generally non-magnetic in the southern Quesnel terrane. Map co-ordinates in UTM Zone 10, NAD 83.

area are punctuated by highs correlated to mapped and interpreted magnetite-bearing intrusive bodies (intermediate to ultramafic composition intrusions; labelled "b" in Figure 6), and geologically recent volcanic rocks belonging to the Chilcotin Group (labelled "c" in Figure 6), which are also magnetite-bearing.

In the northern project area, some intermediate to more mafic phases of the Hogem Batholith are magnetic (labelled "d" in Figure 6). Magnetic highs related to the Hogem Batholith trace southward from the northern end of the batholith eventually undergoing a deflection to the southeast where several isolated magnetic bodies (some mapped at surface, some inferred at depth) may signal the most southern extent of the magnetite-bearing phases related to the batholith (Nelson and Bellefontaine, 1996).

6. Interpretations

Preliminary assessment of geophysical trends indicates broad continuities and provides the basis for an integrated interpretation of geological and geophysical data across the study area.

Recent geological maps from the southern and northern project areas (Schiarizza, 2019; Logan et al., 2020) and Quesnel terrane physical rock property trends underpin interpretations. Geological interpretations are extrapolated from the south northward into more heavily covered areas of the central Quesnel terrane. Observed geophysical trends and their geological interpretations are described here in three sections: south, central, and north QUEST project areas.

6.1. Interpretations – Southern QUEST project area

In the southern project area, recently mapped geology in the Bridge Lake–Quesnel River area by Schiarizza (2019) provides insight into geophysical responses recorded here. In this area, Schiarizza's "assemblage three" of the Nicola Group, characterized by relatively homogeneous pyroxene-phyric basalt, pillow basalt and basalt breccia, correlates with linear gravity highs (Figure 8). These rocks are also resistive, indicative of coherent units with low porosity. A syncline interpreted in this area (Panteleyev et al., 1996, Schiarizza, 2016, Schiarizza, 2019) leads to a mirroring of the linear features across the inferred axial trace. Schiarizza (2019) described the other assemblages making up the Nicola Group in this area as having higher proportions of sedimentary rocks. "Assemblage one" contains siltstone, slate, volcanic sandstone, with lesser coherent volcanic rocks, "assemblage two" contains volcanic sandstone, basalt, basalt breccia, conglomerate, siltstone, limestone, and chert, and "assemblage four" is characterized by polylithic conglomerate and breccia, sandstone, limestone, basalt, and andesite. Based on trends previously noted in geophysical and petrophysical data, sedimentary rock-dominated units should be comparatively less dense and less resistive than more massive volcanic units. Additional linear gravity highs in this part of the project area that

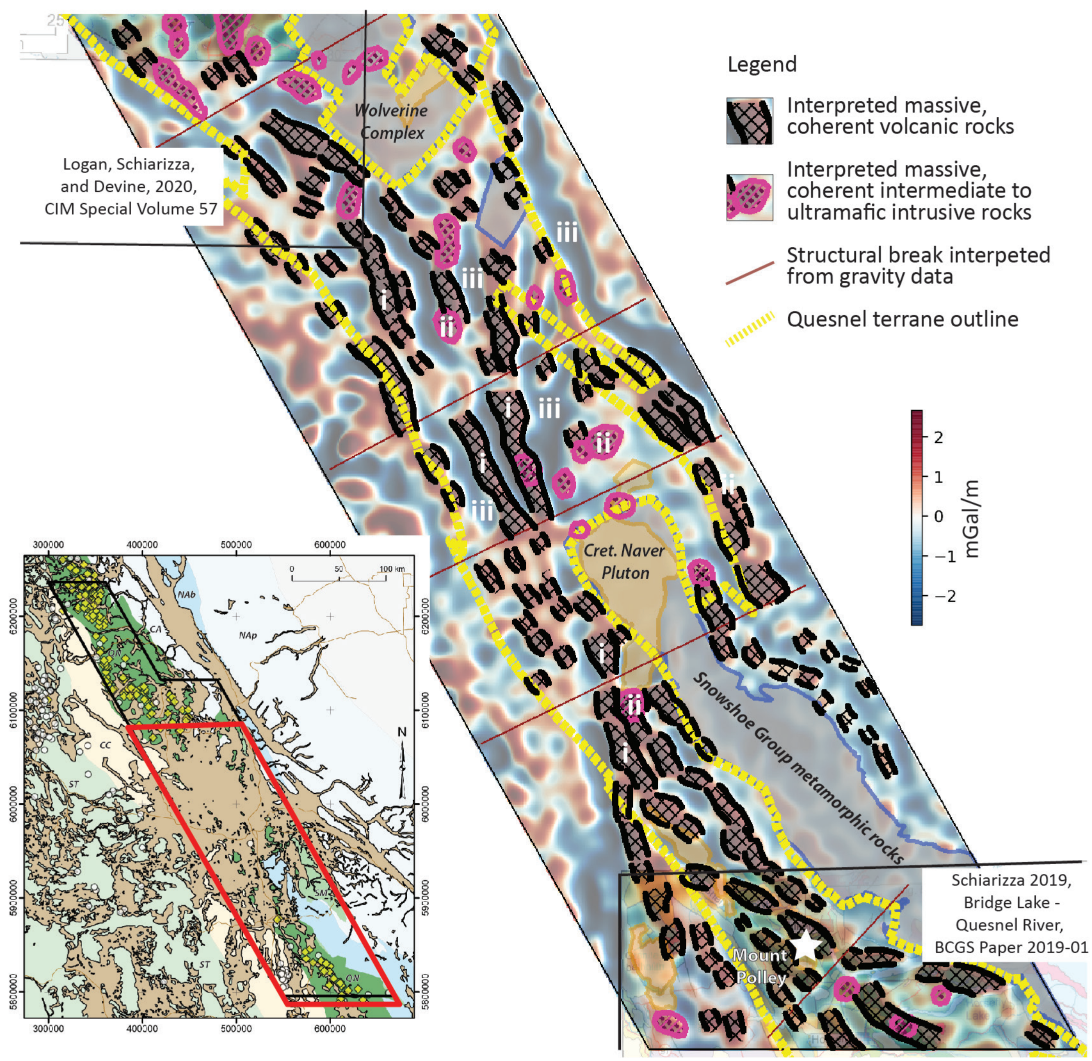

Figure 8: First vertical derivative of Bouguer gravity with bedrock interpretations based on gravity and VTEM data. Positive linear gravity responses trend northwestward from the southern project area, where similar responses correlated with Schiarizza's (2019) "assemblage 3". Similar features to this are indicated in places with "i". Some dense bodies are correlated with mapped intrusions or unmapped anomalies that have the appearance of intrusions, examples of these bodies are labelled "ii". Gravity lows that are also resistivity lows (Figure 5) are correlated with sedimentary rock-dominated assemblages, some examples are indicated on this figure as "iii". Inset location map from Figure 1.

do not align with assemblage three units, may represent more coherent phases of assemblages one, two, and four. Some gravity highs are less linear, and more discrete. These might reflect moderate to high density intermediate to mafic intrusive rocks. This is supported in some areas by the mapped geology.

The Mount Polley porphyry copper-gold deposit is hosted in assemblage four in the core of the syncline (Schiarizza, 2019), close to the axial trace of the inferred NNW trending fold axis. The gravity low underlying the deposit is potentially related to the assemblage four polylithic conglomerates and/or the syenitic intrusive host rocks. The Gibraltar deposit is hosted in low density, high resistivity tonalitic rocks.

6.2. Interpretations – Central QUEST project area

Bedrock geology within the central, and largely sediment-covered parts of the project area can be inferred from trends seen in the southern project area. The linear gravity highs (corresponding primarily with assemblage three) from the Bridge Lake–Quesnel River map area (Schiarizza, 2019) continue trending northwest to approximately the southern end of the Cretaceous Naver Pluton (Figure 9), beyond which they start to become more discontinuous. North of the Naver Pluton, more continuous, linear gravity highs continue northward until the approximate latitude of the center of the mapped extents of the Wolverine Complex, where they appear to break up once again. As in the south, these linear gravity highs alternate with gravity lows. In general, more continuous unbroken gravity highs

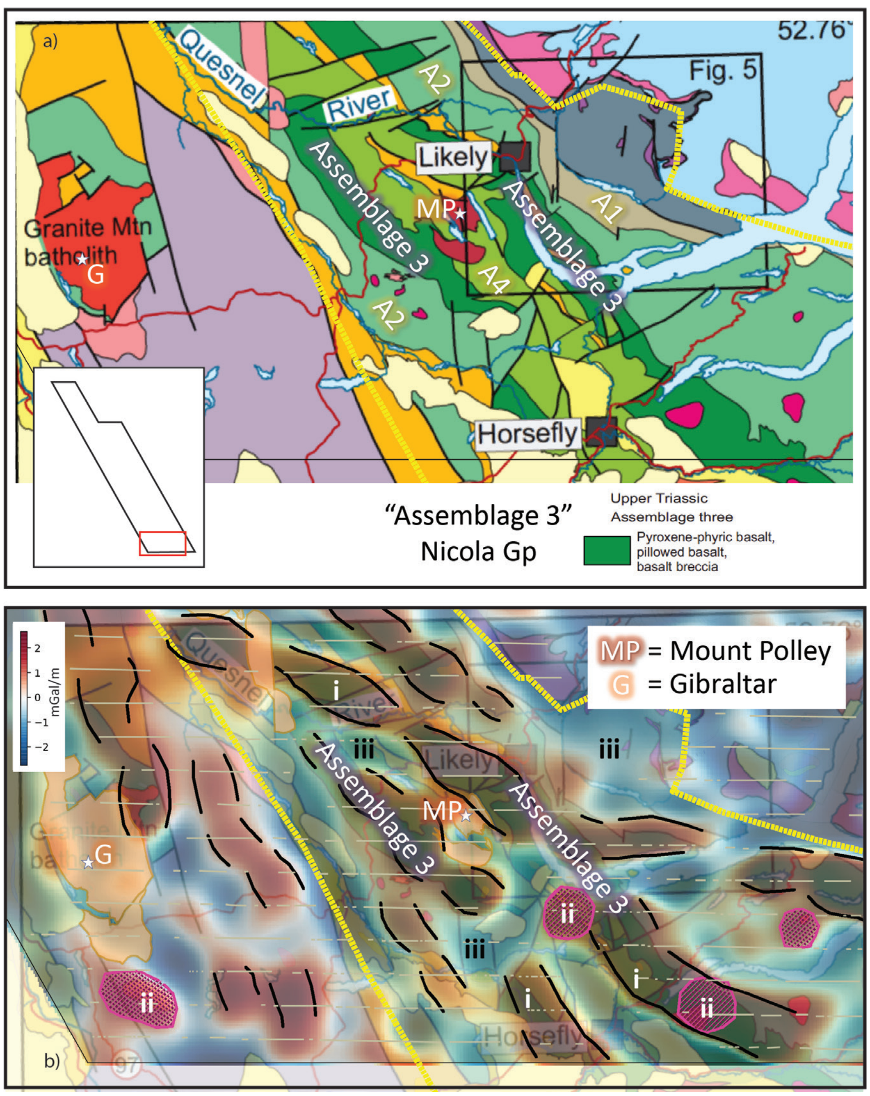

Figure 9: a) Bedrock geology map from the southern QUEST project area modified from Schiarizza (2019). Assemblage 3e from Schiarizza (2019) is highlighted and assemblages 1, 2, and 4 are annotated A1, A2, and A4, respectively. b) First vertical derivative of Bouguer gravity overlain on map shown in (a). Light brown east-west lines are locations of bedrock resistors interpreted from VTEM models. Assemblage 3 is associated with positive gravity responses and high resistivities. Dense and resistive rocks are indicated in places with "i". Some dense and resistive bodies are correlated with mapped intrusions, examples are labelled "ii". Gravity lows are correlated with sedimentary rock-dominated assemblages, examples are labelled "iii". These are generally low resistivity. "Fig. 5" corresponds to an area of detailed mapping from Schiarizza (2019).

occur in the western part of the Quesnel terrane. In the east, areas are dominated by gravity lows, or weak or discontinuous gravity highs.

Although geological maps from the central Quesnel terrane are based on sparse outcrop, some validation of geophysical interpretations can be gained from them. An early map of the geology of the Prince George area from Tipper (1961) shows a spatial relationship between a unit referred to as the Upper Triassic to Lower Jurassic Eastern group (unit 6A) and gravity highs (Figure 10a). This unit is described as consisting of argillite, greywacke, andesite, basalt, and related tuffs and breccias. Pyroxene phenocrysts are not explicitly mentioned, therefore it is not clear whether the Eastern group is correlative with pyroxene-phyric Nicola Group basalts like those of the Bridge Lake–Quesnel River map assemblage three, or possibly, assemblage two.

Struik et al. (1990) updated the geological map of the Prince George area. Broad correlations are noted between Struik et al. (1990) units TJNc, composed of augite porphyry basalt tuff, breccia, minor flows, tuffaceous argillite and siltite, and local andesitic basalt, and the dense and resistive stratigraphy west of the Naver Pluton (Figure 10b). East and north of the Naver pluton, Struik et al. (1990) mapped units TJNa and TJNb. These units are described as being dominated more by volcanic sedimentary facies (basalt tuff, siltite, argillite, slate, greywacke, with no augite-porphyritic units described), and they correlate with a region of interpreted lower densities and lower resistivities from gravity and VTEM data.

As in the southern project area, some of the gravity highs are more discrete and may reflect under cover or deep intrusive rocks. Most of these anomalies coincide with magnetic highs that have been previously interpreted as possible intrusive rocks (e.g., Mitchinson et al., 2022). The apparent high densities of these sources indicate intermediate to ultramafic composition rock bodies.

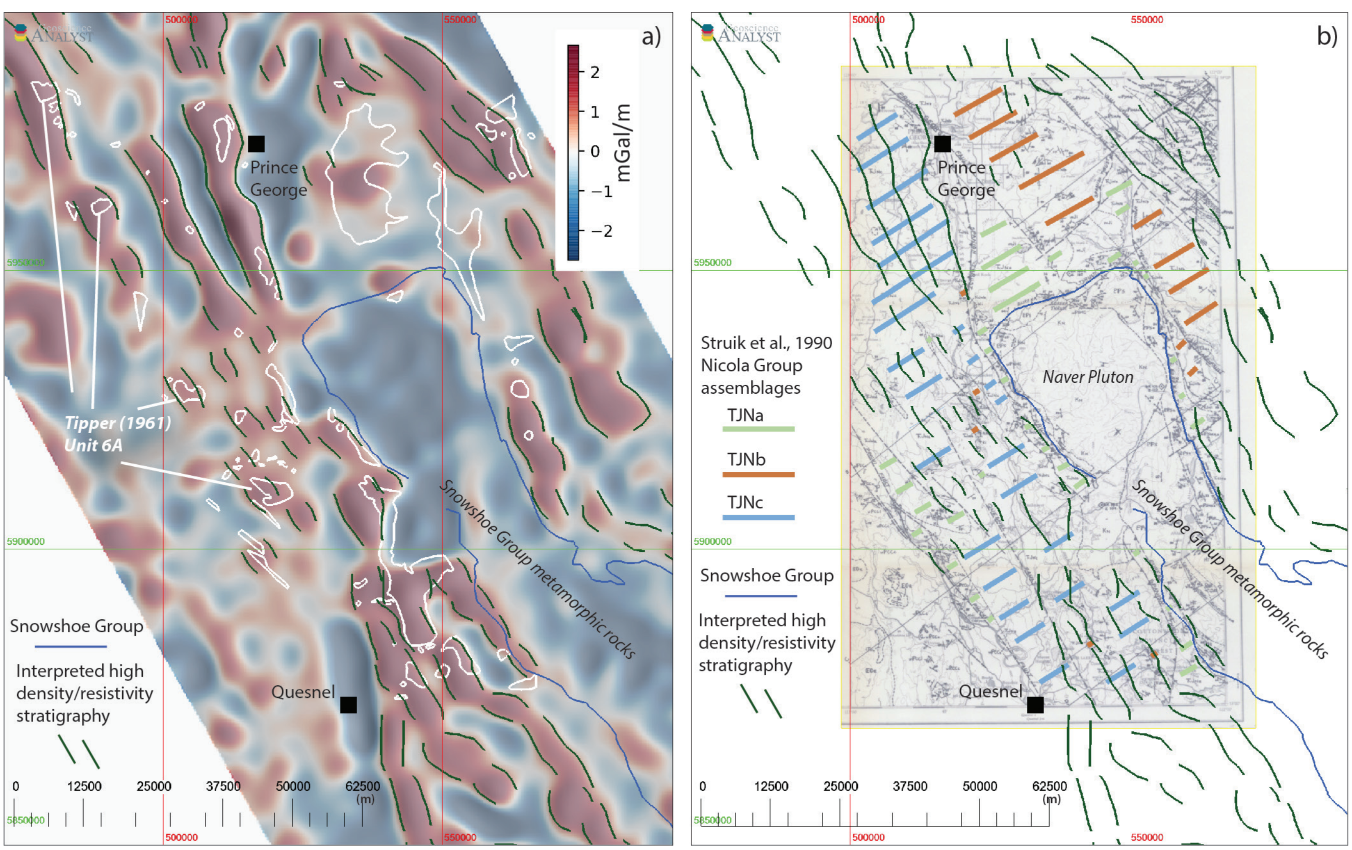

Figure 10: a) First vertical derivative of Bouguer gravity with white polygons representing Tipper's (1961) Unit 6A, which has a close spatial correlation with northwest-trending linear gravity highs. b) Map from Struik et al. (1990) from the same area, indicating relationships between interpreted dense stratigraphy in the west and unit TJNc (blue). Continuous dense stratigraphy is not as prominent in the east where Struik et al. (1990) have mapped units TJNa (green) and TJNb (orange). Map co-ordinates in UTM Zone 10, NAD 83.

6.3. Interpretations – North QUEST project area

At the northern end of the project area, greater topographic variability and less sedimentary cover results in more opportunities to observe and map bedrock geology. The geology of this area was summarized recently in Logan et al. (2020). As in the southern project area, more detailed mapping allows for validation of relationships between Quesnel terrane geology and geophysical features.

The northern project area is dominated by volcanic and intrusive rocks (Figure 11). To the west, intrusive rocks of the Early Jurassic Hogem Batholith trend northwest-southeast, mapped over 150 km on its long axis. The majority of

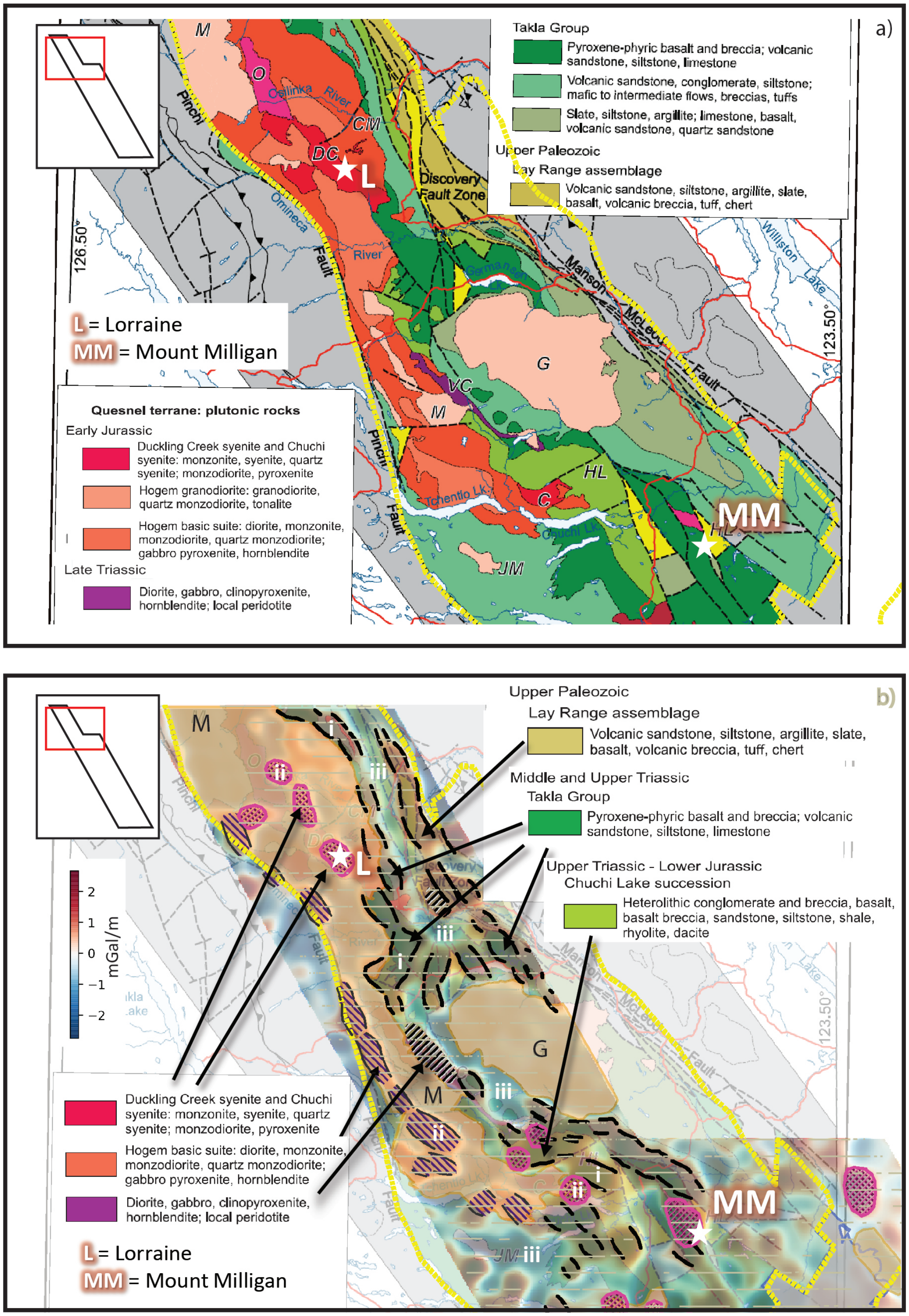

Figure 11: a) Bedrock geology map from the northern QUEST project area modified from Logan et al. (2020). b) First vertical derivative of Bouguer gravity overlain on map shown in (a). Light brown east-west lines are locations of bedrock resistors interpreted from VTEM models. Linear positive gravity highs to the east of the Hogem batholith are correlated with basaltic units of the Lay Range assemblage, the Takla Group, and the Chuchi Lake succession. Examples of these dense and resistive rocks are indicated in places with "i". Some dense and resistive bodies are correlated with mapped intrusions, examples are labelled "ii". Some are within the Hogem Batholith, others occur within the volcanic stratigraphy. Gravity lows in volcanic successions are correlated with volcano-sedimentary rock-dominated assemblages, examples are labelled "iii". Cretaceous intrusions including those associated with the Mesilinka intrusive suite (M), and the Germansen Batholith (G) are resistors correlated with gravity lows.

the batholith is comprised of the Hogem basic and granodiorite suites (Thane Creek units of Ootes et al., 2020), the older Polaris mafic-ultramafic complex and younger Duckling Creek Syenite suite and Heidi Lake suite. The Hogem Batholith is largely resistive, however, there is significant variability in gravity response. Gravity highs in its center correlate with more mafic phases like pyroxenites seen at the Lorraine copper-gold porphyry property, and with the Hogem basic suite mapped along the western edge of the batholith (Figure 11). Hogem basic suite rocks mapped along the eastern edge of the Hogem batholith do not appear to be consistently correlated with a positive gravity response, or they may be interrupted here by less dense units. Hogem granodiorite is consistently associated with gravity lows, as are Cretaceous Mesilinka granitic intrusive rocks ("M" on Figure 11). The Cretaceous Germansen Batholith ("G" on Figure 11) to the east is also correlated with a gravity low. The Cretaceous intrusions are largely resistive bodies.

To the east of the Hogem Batholith, volcanic rocks from the Middle to Upper Jurassic Takla Group lie to the west of Upper Paleozoic Lay Range assemblage volcano-sedimentary rocks. One mapped unit within the Takla Group is dominated by pyroxene-phyric basalt and breccia (colored dark green on Figure 11), and is similar in composition to Schiarizza's (2019) assemblage three in the Bridge Lake–Quesnel River map area in the south. There is a correlation between the mapped occurrences of this unit, linear gravity highs, and VTEM resistors. Additional linear gravity highs correlate with Upper Paleozoic Lay Range rocks, and with the Upper Triassic-Lower Jurassic Chuchi Lake Succession presumably where these units are dominated by more massive, coherent rocks (Figure 11). As in the south, linear gravity and resistivity highs alternate with gravity and resistivity lows. The gravity-resistivity lows appear to map volcanic sediment-dominated units of the Takla Group. The linear gravity-resistivity highs are fairly continuous from the top of the project area to south of the Germansen Batholith, where they eventually break up near the approximate latitude of the Mount Milligan deposit. This belt of alternating linear gravity highs and lows, resembles patterns seen in west-central Quesnel terrane.

Other discrete gravity highs within mapped or interpreted volcanic stratigraphy here seem to correlate with mapped or indicated intermediate to ultramafic intrusive bodies, some of these correlated to mineral occurrences.

7. Discussion

Figure 12 shows an interpretation of the distribution of regional volcano-sedimentary and intrusive units and domains based on interpretation of QUEST project gravity and VTEM data from the central Quesnel terrane.

The trends in gravity and VTEM data support previous mapping and observations documenting basin-fill successions in the eastern Quesnel terrane and constructional volcanic facies and proximal volcaniclastics in the west (Panteleyev et al., 1996; Schiarizza, 2019). Gravity and VTEM data suggest eastern Quesnel terrane rocks are less dense and less resistive (more conductive) implying a more porous or permeable, dominantly sedimentary rock package. In the west, pyroxene-phyric volcanic flows and related breccias are dense and resistive.

Gravity and VTEM data indicate that stratigraphy, characterized by bands of relatively massive, coherent rock adjacent to less massive, more porous or permeable rock, trends in a northwesterly direction from the area around the Mount Polley copper-gold deposit to about 40 km north of Fort St. James. The alternating gravity and resistivity highs and lows in the western parts of the Quesnel terrane are interpreted to reflect a broadly folded and faulted volcanic stratigraphy, leading to coherent massive volcanic units and less coherent sedimentary rocks being juxtaposed (e.g., cross-sections from Struik et al., 1990). North- to northwest-trending linear gravity and VTEM anomalies continue northward along the eastern margin of the Hogem Batholith.

In the eastern project area, the geophysical anomalies related to the volcanic stratigraphy are interrupted by exposures of older Proterozoic to Paleozoic Snowshoe Group metamorphic rocks and the Wolverine Metamorphic Complex, and because of this are more difficult to trace and correlate with units mapped in the north and south. In the region between the Wolverine Complex and the Snowshoe Group, gravity anomalies are less continuous, suggesting

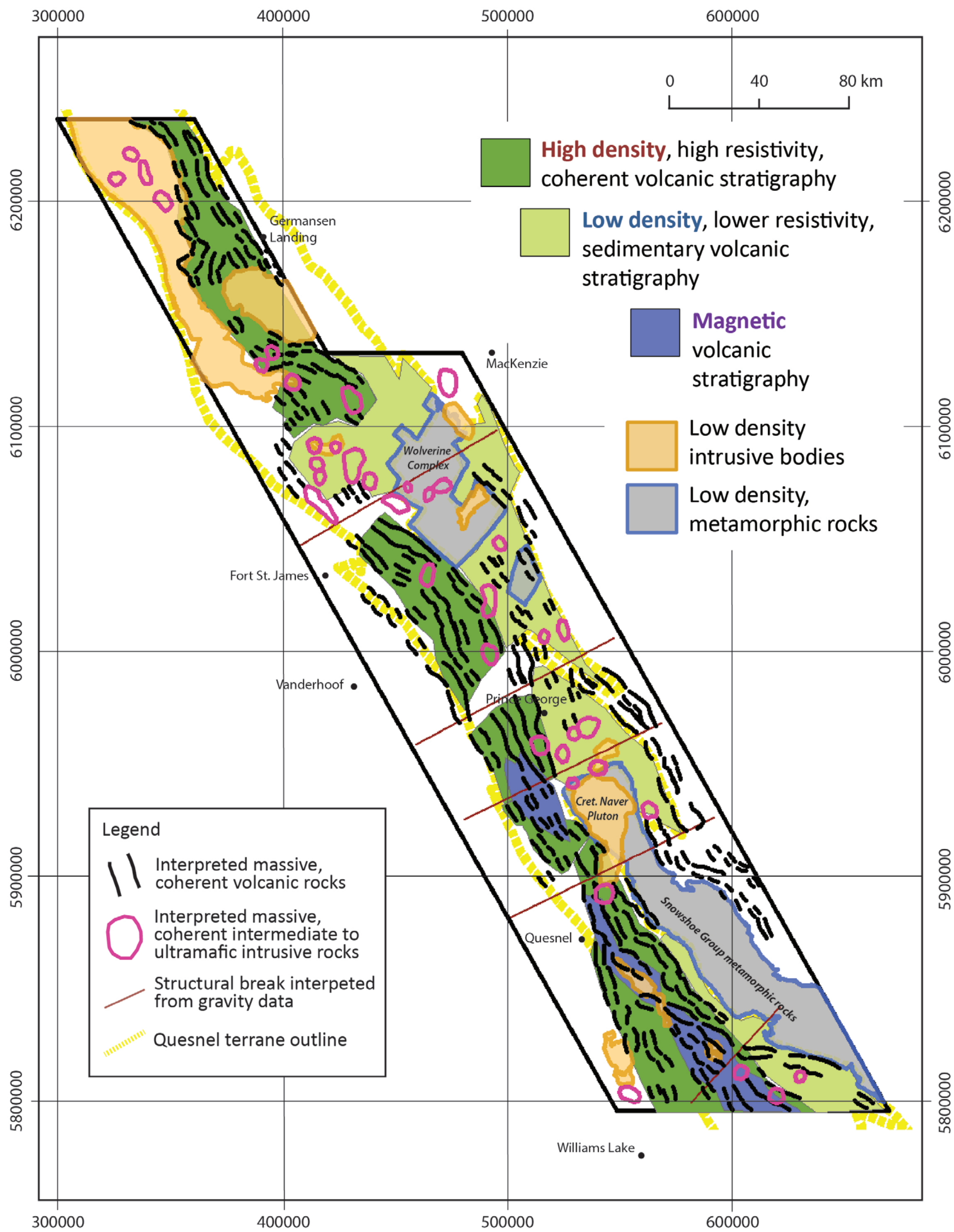

Figure 12: Schematic summary of major volcano-sedimentary and intrusive domains making up the bedrock of the QUEST project area interpreted from QUEST gravity and VTEM data. Map co-ordinates in UTM Zone 10, NAD 83.

less coherent sedimentary rock-dominated domains, or more structurally disrupted, or hydrothermally-altered rocks (destroying dense and resistive minerals).

The linear gravity-resistivity features appear to be disrupted along strike by southwest-trending breaks in a few areas. From south to north, the first major break in the trend of linear features aligns with the southern end of the Cretaceous Naver Pluton, and the second correlates with the northern end of the same pluton. A third break in the trend occurs about 15 km north of Prince George. A fourth break occurs aligned with the northern mapped margin of the Wolverine Complex. The strike of these 'breaks' is consistent with Eocene age extensional structures (Struik, 1993). This study did not definitively identify correlations between known mineralization or possible prospective intrusions and major structures, but the actual distribution of porphyry deposits in the central Quesnel terrane is unknown due to limited exploration there. Faults are, however, known to play important roles in the localization of porphyry deposits (Richards, 2000; Tosdal and Dilles, 2020). Arc-oblique structures have been identified as spatially correlated to porphyry deposits in ancient and modern volcano-magmatic arc environments (White et al., 2014; Piquer et al., 2016; Farrar et al., 2023). The intersection of these structures with arc-parallel fault zones creates conduits for magma, and space for enhanced magmatic-hydrothermal fluid flow. Southwest-trending breaks apparent in the gravity data from central BC could benefit from further investigations and integration with structural knowledge of the area. The somewhat regular spacing of porphyry deposits in the southern Quesnel terrane (Logan and Mihalynuk, 2014), south of the project area, indicate a regular structural disruption along the strike of the southern part of the arc. Adjacent Late Triassic and Early Jurassic intrusions there, some of which host porphyry mineralization, suggest that structural weaknesses are possibly re-exploited. Southwest-striking structures interpreted from geophysics parallel Eocene age faults in the central Quesnel terrane, but this should not rule out a longer-lived fault system. In Chile, arc-oblique structures linked to localization of porphyry mineralization are considered to follow ancient structural corridors initially active in the Mesozoic (Pique et al., 2016; Farrar et al., 2023) and reactivated in the Eocene-Oligocene. It would be of interest to conduct further research on arc-oblique central Quesnel structural breaks, including application of higher resolution or complimentary deep-imaging geophysical methods like magnetotelluric (MT) or seismic surveys, in addition to trying to identify these or similarly striking features in the field.

Magnetic volcanic stratigraphy is present in the southern half of the project area. Presumably the positive magnetic response of these rocks is due to the presence of magnetite, the most common magnetic mineral in rocks. The magnetic stratigraphy continues southward beyond the project area, for approximately 75 km. South of this, the volcanic rocks of the southern Quesnel terrane of BC are dominantly non-magnetic. The magnetic map patterns suggest there are compositional differences between volcanic source magmas from the southern to the northern project area. This is consistent with trends noted in Nicola Group and Takla Group volcanic rocks from various locations within the Quesnel terrane by Vaca (2012). Vaca showed that the magnetic Nicola Group volcanic rocks sampled are oxidized, and in the case of Mount Polley area samples, closely related in age to oxidized intrusions hosting porphyry copper-gold mineralization. In the north, non-magnetic volcanic rocks may be derived from a more reduced magmatic source. Considering physical properties alongside lithogeochemistry and mineral chemistry, Vaca (2012) implies there were different melting conditions occurring along the arc which may have led to these variable oxidation states and lithologic compositions.

Rounded isolated bodies with coincident gravity and magnetic highs occur across the project area. These have been interpreted by Mitchinson et al. (2022) as intermediate to ultramafic intrusive bodies geophysically resembling host rocks to known alkalic copper-gold porphyry deposits in British Columbia. Some of these bodies are correlated with outcropping or drilled intrusive rocks and others are untested or possibly occur at depth. As previously mentioned, in the southern Quesnel terrane, there is a noted arc-parallel regular spacing of late Triassic alkalic intrusions that are known hosts to porphyry copper-gold mineralization (Panteleyev et al., 1996; Logan and Schiarizza, 2011; Logan and Mihalynuk, 2014). The intrusive bodies interpreted during this study do not seem to follow the roughly regular along-strike spacing of Triassic intrusions documented in the southern Quesnel terrane. Nor do they appear to occur mainly along the axis of apparent constructional volcanic activity where they commonly occur in the southern Quesnel terrane as described by Panteleyev et al. (1996). In the central Quesnel terrane, these occur mainly in the lower gravity and lower resistivity rocks of the east, with fewer instances in the interpreted massive volcanic stratigraphy to the west. Rogers (2021) has suggested that intrusions of Triassic to Jurassic age may not consistently occur at predictable intervals or within specific volcanic belts or units outside of the southern Quesnel terrane if intrusions have been subsequently displaced due to faulting, or if magmatism did not occur consistently along the belt. Intrusive bodies of ages similar to known porphyry deposit hosts in the northern and southern Quesnel terrane should be considered of interest in regional exploration, regardless of the substrate in which they are emplaced.

Jurassic calc-alkalic intrusions in southern Quesnel are characterized by large gravity lows, indicating low density mineral compositions. Similar large gravity lows are not seen in the central Quesnel terrane (QUEST area), with the exception of the Hogem Batholith, and gravity lows associated with more recent Cretaceous plutons. This could suggest less calc-alkalic magmatic activity focused in the central Quesnel terrane, or different erosional levels compared to the northern and southern Quesnel terrane, although a large low density intrusive body even at significant depth should be identifiable in gravity data if present.

8. Conclusions

The Jurassic to Triassic volcanic arc rocks of the Quesnel terrane of British Columbia contain rich copper and gold resources. With six operating mines in the Quesnel terrane, it's the source of approximately half of Canada's annual copper production. Parts of the Quesnel terrane, however, are under-explored due to extensive sedimentary cover deposits hindering bedrock mapping and sampling, and deterring drillers. The QUEST project initiated by Geoscience BC in 2007 saw electromagnetic (VTEM) and gravity surveys completed over the most extensively covered parts of the central Quesnel terrane. This provided new data for interpretation of geology under cover. These data had not undergone significant interpretation to this point. The data are shown to be very effective for mapping regional scale volcanic, sedimentary, and intrusive geologic domains. Commonly, magnetic data are used for remote interpretation of bedrock geology when areas are under sedimentary cover or difficult to access. But since volcanic stratigraphy in the project area has only a weak magnetic response, magnetic data are not as useful here for mapping volcanic domains. Gravity and VTEM data on the other hand, although lower resolution, identify contrasting volcanic domains through sediment-covered areas.

Comparing VTEM and gravity data with recent geological maps validates its use in mapping volcanic stratigraphy. While it is not possible to assign interpreted stratigraphic domains to classifications used on current bedrock maps or in the BCGS bedrock geology database, we can gain an understanding of the composition and coherency of the bedrock. Geophysical interpretations of bedrock geology through the central Quesnel terrane indicate that dense and resistive stratigraphy correlate with previously mapped pyroxene-phyric volcanic units and dominate the western part of the terrane. Lower density, lower resistivity rocks correlating with previously mapped basin-fill sedimentary rocks dominate in the east. A compositionally different series of volcanic rocks, containing magnetite and thus producing a positive magnetic response, occurs in the southern part of the project area and extends southward and may be derived from a different magmatic source compared to volcanic rocks in the northern and southern Quesnel terrane. Isolated bodies that correlate with gravity, resistivity and magnetic highs are possible intermediate to ultramafic composition intrusive rocks. Known alkalic-type porphyry deposits in the Quesnel terrane are usually hosted in high density, high magnetic susceptibility, intermediate composition intrusions (Mitchinson et al., 2022), and these interpreted bodies may represent targets to focus greenfield porphyry deposit investigations. If further investigations of previously unsampled dense and magnetic anomalies uncover mafic to ultramafic intrusive sources, they could alternately be investigated as potential hosts to magmatic nickel-copper style deposits.

The integrated geological and geophysical interpretations completed as part of this study add value to underutilized QUEST gravity and VTEM geophysical datasets by extrapolating more well-understood geology from the northern and southern Quesnel terranes into the sedimentary deposit covered central Quesnel terrane, where bedrock geology is difficult to map. Gravity and electromagnetic data interpretations provide a framework for an evolving understanding of the magmatic and tectonic history of the Quesnel terrane, and offer further insight into obscured and deep bedrock geology, providing context for mineral exploration in this highly prospective mineral belt.

9. Project Deliverables

Compressed (.zip) file with:

- Geoscience Analyst 3D project
- Shapefiles of geological and structural features interpreted from VTEM models and gravity data (polygons and polylines)
- 3D bedrock resistors from VTEM interpretations as .dxf files

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