Toward an Improved Basis for Beneath-Cover Mineral Exploration in the QUEST Area, Central British Columbia: New Structural Interpretation of Geophysical and Geological Datasets (NTS 093A, B, G, H, J, K, N)

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Introduction

Geoscience BC's QUEST survey area in central British Columbia (Figure 1) has a large amount of regional geophysical and geochemical data available to the exploration industry; however, despite the wealth of data, the bedrock geology remains poorly constrained, especially in the extensive areas covered by glacial drift in the Prince George area. The area is generally prospective for porphyry Cu-Au mineralization beneath covering glacial drift. Previous attempts to integrate geophysical, geochemical and geological information to constrain the geology beneath cover (Logan et al., 2010) provided results that were heavily biased toward interpolation between known outcrops and failed to take into consideration much of the geophysical and geochemical evidence. Moreover, this bedrock geology interpretation could only be poorly reconciled with new outcrops documented recently (Bissig et al., 2011) during ground-truthing of maps based on neural-network processing of stream and lake-sediment geochemical data (Barnett and Williams, 2009). The existing map interpretations from Logan et al. (2010) and Barnett and Williams (2009) are vastly different and neither considers the structural fabric evident from magnetic data. This project aims to improve previous geological maps by using a new and systematic multi-dataset 'stacking' methodology (Sánchez et al., 2014) for the interpretation of Geoscience BC's Bouguer and isostatic residual (IR) gravity grids, Natural Resources Canada's (NRCan) regional reduced-to-pole (RTP) aeromagnetic data (Figure 1b, c) and the satellite-derived Shuttle Radar Topography Mission (SRTM) digital elevation model. The new structural and geological interpretation will provide a fresh look at the bedrock geology in this highly prospective terrain and will contribute to the generation of new exploration targets.

Keywords: *QUEST, structure, geophysics, magnetometry, gravity, mineral exploration*

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Geological and Metallogenetic Framework

The QUEST project area is focused on the Quesnel and Cache Creek terranes, which are part of the Intermontane (or Peri-Laurentian) tectonic realm (Monger et al., 1982; Nelson et al., 2013) and the western part of ancestral North America (Laurentian realm; Nelson et al., 2013; Figure 1). The latter contains orogenic and placer Au mineralization that, in the QUEST area, is concentrated most importantly in the historical Wells-Barkerville camp (Figure 2b). The Quesnel terrane is composed largely of Triassic volcanic and volcano-sedimentary rocks of basaltic composition assigned to the Nicola Group and along-strike equivalent Takla Group (Mortimer, 1987; Nelson et al., 2013; Figure 2c). These rocks represent an oceanic-arc assemblage and vary from alkalic to calcalkalic and tholeiitic. The Nicola and Takla groups host late Triassic to early Jurassic alkalic Cu-Au porphyry deposits, such as Mount Polley and Mount Milligan (Jago et al., 2014; Pass et al., 2014; Figure 2c). Located west of the Quesnel terrane, the oceanic Cache Creek terrane includes shale and deep water limestone, basalt and ultramafic complexes (e.g., Massey et al., 2005; Nelson et al., 2013; Figure 2d). The Peri-Laurentian terranes were accreted to the North American continent during the early Jurassic, during which time the alkalic Cu-Au porphyry deposits of Mount Milligan and Lorraine were emplaced (e.g., Devine et al., 2014; Figure 1). The southwestern part of the QUEST area includes some of the Nechako Plateau, a domain containing thick sequences of late Cretaceous to Eocene volcanic deposits that are prospective for epithermal mineralization (Bordet et al., 2014; Figure 1a).

Datasets

The structural and geological interpretation in this study uses Geoscience BC's airborne gravity grid, NRCan's aeromagnetic grids (Geoscience BC, 2009a) and the SRTM90v3

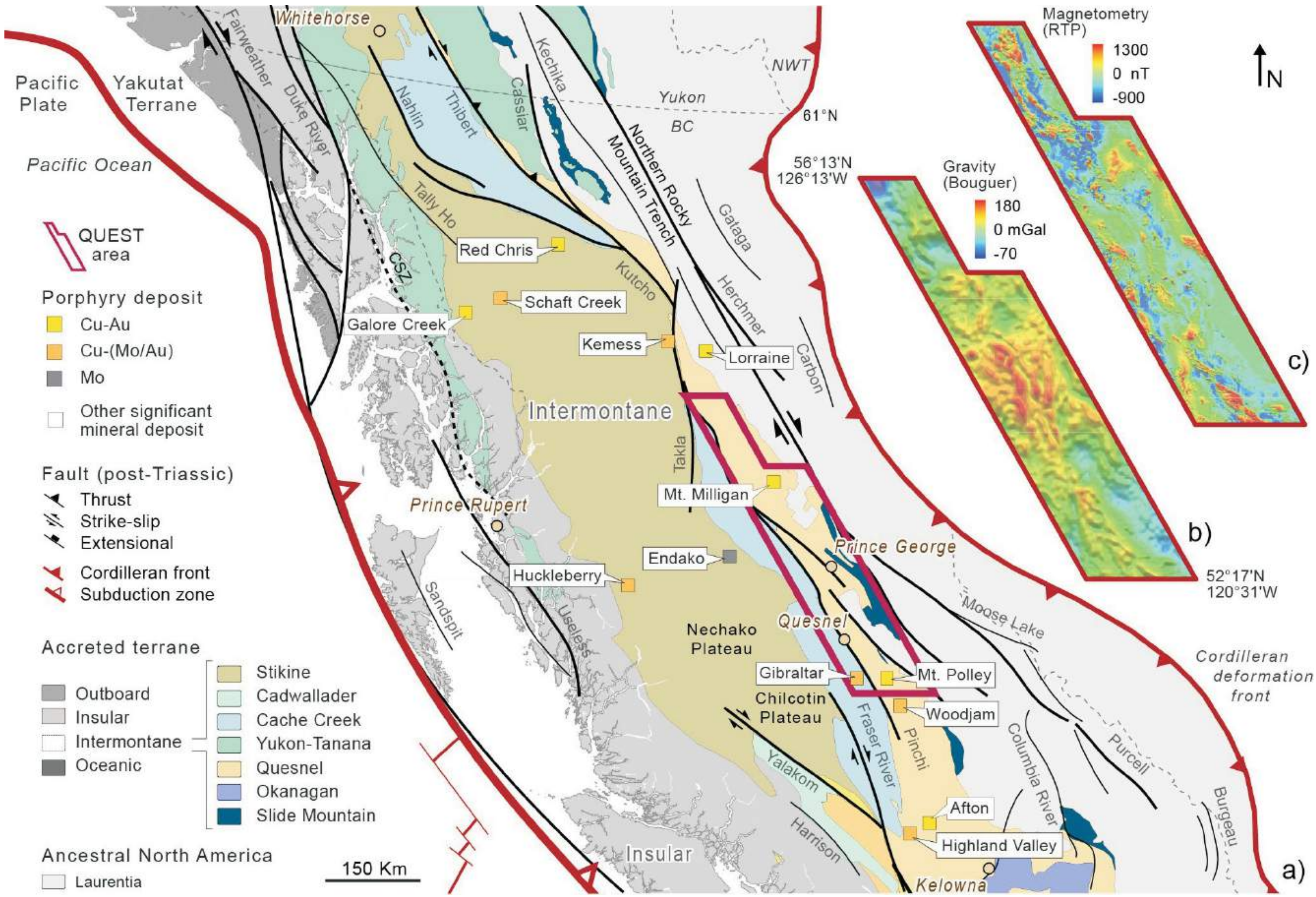

Figure 1. a) Tectonic map of the North American Cordillera of British Columbia, showing major tectonic boundaries (after Colpron and Nelson, 2011), Mesozoic and Cenozoic faults, and main porphyry-style mineral deposits. **b)** Geoscience BC's airborne gravity grid. **c)** Natural Resources Canada's aeromagnetic grids (Geoscience BC, 2009a). Location of (b) and (c) shown by red outline in (a). Abbreviations: RTP, reduced-to-pole.

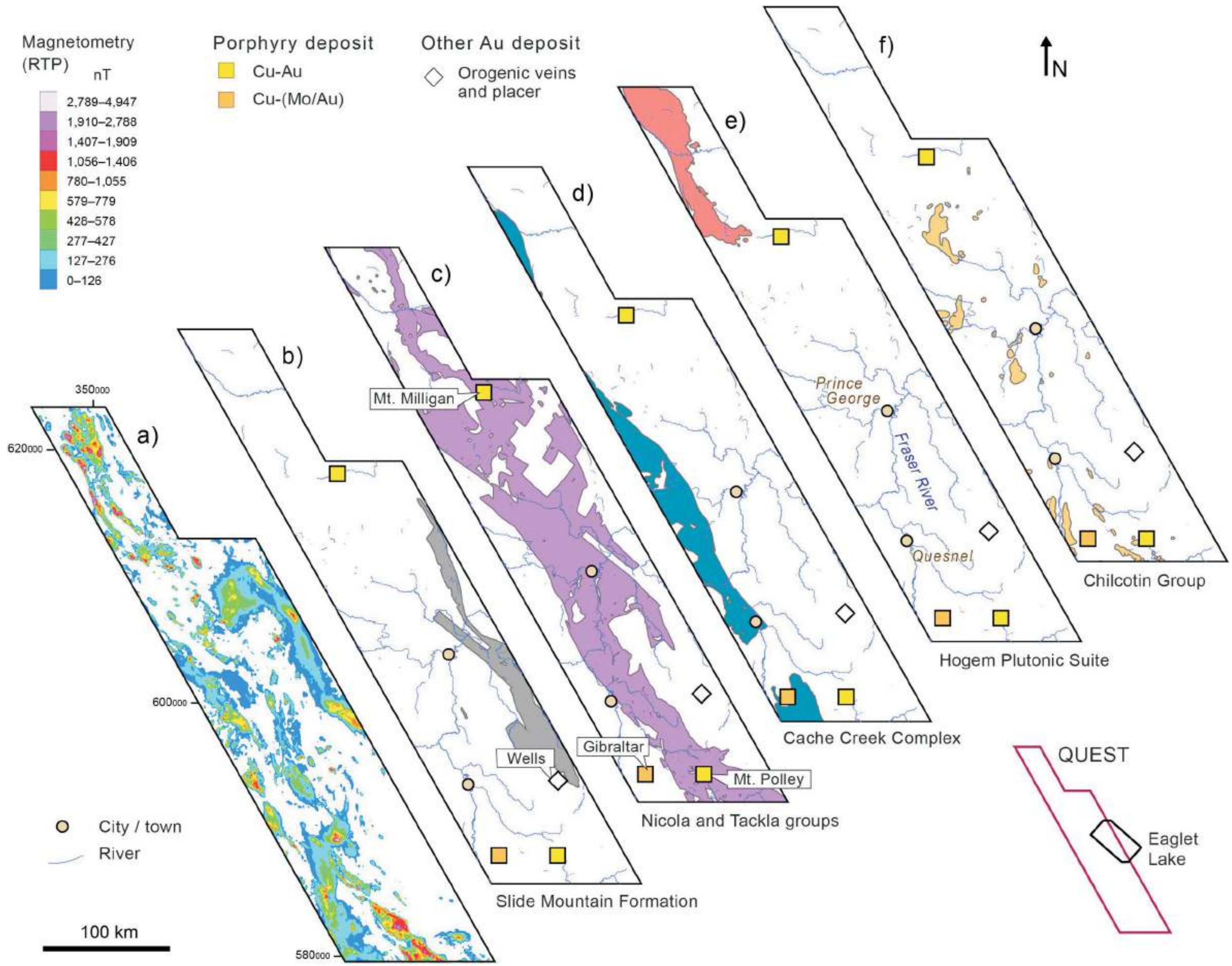

Figure 2. Reduced-to-pole (RTP) aeromagnetic anomalies and their correlation with principal geological units of the QUEST project area (Geoscience BC, 2009b), showing also the spatial distribution of porphyry deposits: **a)** positive-intensity RTP aeromagnetic grid; **b)** to **f)** major geological units with a magnetic response.

digital elevation model (Farr et al., 2007). All remotely sensed datasets have been jointly interpreted with the 1:1 000 000 surface geology map published by the BC Geological Survey (Massey et al., 2005) and the 1:500 000 scale QUEST project geology map (Geoscience BC, 2009b; Figure 2b–f). Geophysical acquisition for Geoscience BC's QUEST project began in 2007 and included an airborne electromagnetic (EM) survey (not used in this study) and an airborne gravity survey, which covered an area of approximately 150 000 km^2 between Williams Lake and Mackenzie in northeastern BC (Figure 1; Barnett and Kowalczyk, 2008). The high-resolution airborne gravity survey was conducted by Sander Geophysics Ltd. (SGL) in 2007 and 2008 (Sander Geophysics Ltd., 2008). It consisted of 27 480 line-km, with traverse lines spaced at 2000 and 1000 m intervals oriented at 090° and control lines at 20 km spacing and oriented at 150.5°. The survey was flown using SGL's Airborne Inertially Referenced Gravimeter (AIRGrav) system at a nominal terrain clearance of 200 m. Three final airborne gravity grids were released by Geoscience BC (Geoscience BC, 2009a): a Bouguer anomaly map, an isostatic residual (IR) map and a first vertical derivative (1VD) map. The aeromagnetic data used in this project consist of a seamless mosaic assembled by Geoscience BC using data from NRCan (Geoscience BC, 2009a). Most airborne magnetic surveys in this unified grid were flown on east-trending flight lines at a line spacing of 805 m and gridded at an interval of 250 m (Barnett and Kowalczyk, 2008). Three final aeromagnetic grids were released by Geoscience BC (Geoscience BC, 2009a): a total magnetic intensity map, a reduced-to-pole (RTP) grid and a potential map grid.

Upward Continued Residual Filters

In order to represent depth surfaces in potential-field data, upward-continued datasets were produced following a methodology similar to the one proposed by Jacobsen (1987), whereby a band-pass filter is used to separate causative sources at various depths. The method implies that, in order to isolate a regional field at a given depth (z0), the observed field is upward-continued to a height above the land surface equivalent to twice its depth ($2 \times z0$). For the definition of upward-continued residual levels, the authors followed the recommendations of Gunn (1997), which emphasize the use of geological constraints at the expense of spectral information (Spector, 1985). Three upward-continuation levels were selected for brittle crustal conditions of less than ~10 km depth. In accordance with a typical geothermal gradient of 30°C/km (Dragoni, 1993), these levels are located well below the Curie temperature of magnetite (585°C) and have the potential to generate a magnetic response. Previously known geological constraints, such as maximum thickness of Quaternary drift cover and of the Chilcotin Group volcanic rocks (Andrews and Russell, 2010), were essential for the definition of shallower depth slices (Figure 2).

The selection of three upward-continued levels is based on the following geological criteria:

- **500 m to 0 m (depth slice from surface to ~250 m):** This range includes the maximum thickness of Quaternary drift cover (~200 m; Andrews and Russell, 2010), as well as Miocene–Pleistocene Chilcotin Group basalts (≤200 m; Andrews and Russell, 2010; Figure 2f). This residual range is proposed to assist in the interpretation of very shallow and lowermost order structures. However, the signal's very short wavelength is highly sensitive to linear artifacts, which need to be carefully assessed throughout the interpretation process.
- **1000 m to 500 m (depth slice from ~250 m to ~500 m):** This residual depth range is intended to suppress the magnetic signal of the Chilcotin Group volcanic rocks and Quaternary drift. It highlights the magnetic fabric of metamorphic foliation, as well as magnetic lineaments of near-surface, lower order, steeply dipping faults.
- **5000 m to 1000 m (equivalent to a ~500 m to ~2500 m depth slice):** This is the depth range for shallow upper crust with Mesozoic plutons and Mesozoic and Paleozoic metamorphic assemblages that commonly occur below unmetamorphosed Cenozoic volcanic and sedimentary rocks. This residual slice is intended to provide valuable information on the magnetic signal of principal northwest- to north-northwest-trending faults that occur subparallel to the main Cordilleran tectonic fabric and principal plutonic belts. It also has the potential to depict the distribution and edges of major gravity and magnetic domains.

Interpretation Method

The current methodologies for structural and geological interpretation focus primarily on high-frequency and variable-intensity aeromagnetic lineaments that correspond to discontinuities with an aeromagnetic domain change (Sanchez et al., 2014). The interpretation of magnetic- and gravity-domain boundaries was further corroborated by their correlation with major geological units. Aeromagnetic lineaments and domain boundaries were first manually traced by using two pairs of high-pass filters: 1) analytic signal (AS) in combination with the horizontal-gradient magnitude (HGM) grid, and 2) 1VD grid in addition to the tilt-derivative (TD) filter. All four filters suppress deep, long-wavelength signals and accentuate or sharpen the near-surface responses that are useful for structural interpretation in drift- and/or basalt-covered areas (Gunn et al., 1997; Milligan and Gunn, 1997). The AS filter and the HGM grid help detect magnetic- and gravity-anomaly boundaries because both filters place their 'peak' amplitude signal over edges or geological contacts. Furthermore, as the amplitude of the AS signal is always positive, it works as an effective antiremanence tool (Gunn, 1997). The 1VD grid and the TD filter are effective in accentuating the high-frequency signals that commonly arise from linear features such as faults, fractures, stratification, foliation and dikes. All four high-pass filters are valuable tools for the textural characterization of magnetic and gravity domains.

For the delineation of gravity and magnetic domains, and their correlation to geological units, the study focused on the interpretation of the previously described upward-continued residual levels. These low-pass filters were used in addition to a series of pseudogravity (PG) grids for non- and upward-continued RTP magnetic residuals. The PG transformation implies an approximate conversion of magnetic to gravity data by changing its rate of decay from the inverse cube of the distance to source to the inverse square of the distance to source (Hildenbrand, 1983).

The structural interpretation in this study is based on a systematic, multi-dataset 'stacking' methodology, in which lineaments are compared against various data layers to provide a measure of geological confidence. In order to evaluate the reliability of the lineament interpretation, individual magnetic lineaments were classified by assigning binary numeric values, depending upon whether they can be traced in each individual grid (Sánchez et al., 2014). The summation of these values results in a reliability scale with which most probable structures were detected. Values were then evaluated against other spatial parameters, such as fault orientations, lineament length, normalized length and line densities. Offsets across magnetic lineaments were then inspected in map-view and cross-section. Finally, results were assessed against known local structural types and the regional structural and tectonic framework for the classification of magnetic lineaments into fault types and systems (Sánchez et al., 2014).

Preliminary Regional Observations

The Nicola Group and laterally equivalent Takla Group, the most widely occurring mafic rocks in the QUEST area, are accurately depicted by the unfiltered RTP grid (Figure 2a, c) and by the longer wavelength, ~500 m to ~2500 m depth-equivalent residual. This residual slice provides valuable information on principal northwest- to north-northwest-trending faults that run subparallel to the main Cordilleran tectonic fabric and the distribution of Mesozoic and Early Cenozoic intrusive rocks. Early Jurassic intrusive rocks from the Hogem Plutonic Suite are the most significant magnetic sources across the northernmost part of the QUEST area (Figure 2a, e). In the central and southern parts, northwest-trending linear magnetic anomalies from Cache Creek's serpentinite sources, as well as scattered magnetic anomalies sourced from basalts, gabbro and diorite from the Slide Mountain Complex, are evident from the RTP grid (Figure 2a, b, d). Ongoing interpretations indicate that northwest- to north-northwest-trending structures and metamorphic fabrics linked to principal fault systems are well represented in all depth-equivalent slices. A series of younger, north- and northeast-trending, steeply dipping faults, which commonly displace orogen-parallel north-northwest-trending structures, is also highlighted.

Structural and Geophysical Interpretation of the Eaglet Lake Area

The Eaglet Lake area, located 30 km northeast of Prince George, serves as a case study for the work discussed herein. This area offers reliable field evidence of northwest- and northeast-trending, steeply dipping brittle faults and fractures (Figure 2). Remotely sensed data interpretation indicates that regional-scale, northwest-trending aeromagnetic lineaments bound a 40 km long aeromagnetic anomaly that is cut and offset by northeast- to east-northeast-oriented, normal to oblique sinistral-normal faults (Figure 3). The aeromagnetic high is overlapped by Cretaceous and Eocene plutons that crop out mainly as northeast-trending, elongated (in plan-view) bodies.

Field observations at a quarry located immediately west of Eaglet Lake (Figure 3) show at least two northwest-trending, plagioclase- and K-feldspar–phyric felsic dikes with disseminated pyrite intruding nonfoliated basaltic rocks of the Slide Mountain Complex (Figure 4a). These approximately 5 m thick dikes occupy subparallel dilational joints with dextral strike-slip reactivation (Figure 3, location 2; Figure 4b). Along the northwestern flank of Eaglet Lake, a series of subparallel, northwest-dipping, dilational quartz veins with epidote and chlorite haloes occupies northeast-trending dilational fractures that are oriented nearly orthogonal to the felsic dikes and dextral strike-slip faults (Figure 3, location 3; Figure 4c). Both dikes and quartz veins occur in the vicinity of a major granodiorite pluton of Eocene age that shows a dense arrangement of planar, southeast-dipping dilational fractures conjugate to the quartz veins and fault/fracture sets (Figure 3, location 3; Figure 4d; Geoscience BC, 2009b).

The authors infer that the Eaglet Lake basin is bounded by a southeast-dipping, normal to oblique sinistral-normal master fault that, in combination with an antithetic, northwest-dipping normal fault, accommodates a 40 km long, northeast- to east-northeast-trending half graben (Figure 3). The most prominent Eocene pluton of the Eaglet Lake area crops out within the Eaglet Lake graben and along its master faults, suggesting syn- to postemplacement control by extensional to oblique-sinistral faults.

Future Work

In order to fully integrate airborne magnetic and gravity datasets, as well as structural-geomorphology interpreta-

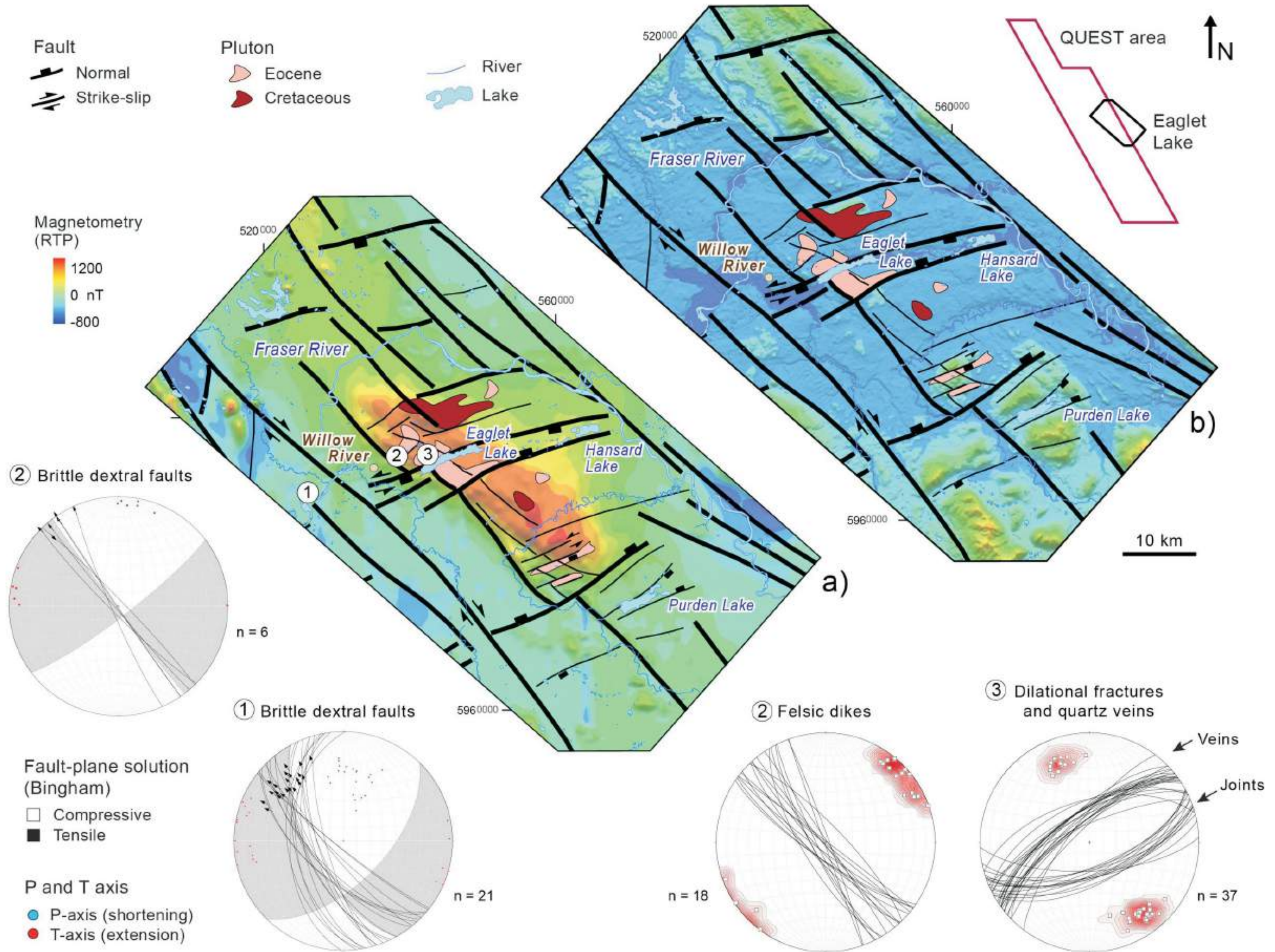

Figure 3. Structural interpretation of aeromagnetic **(a)** and geomorphology **(b)** datasets of the Eaglet Lake area, east of Prince George. Principal northwest-trending, strike-slip faults bound a 40 km long aeromagnetic anomaly that is cut and offset by northeast- to east-northeast-oriented, oblique sinistral-extensional faults that accommodate the Eaglet Lake basin. Field-based structural measurements are shown as stereoplots, the locations of which are indicated by numbers in map (a). Plutons modified after Massey et al. (2005).

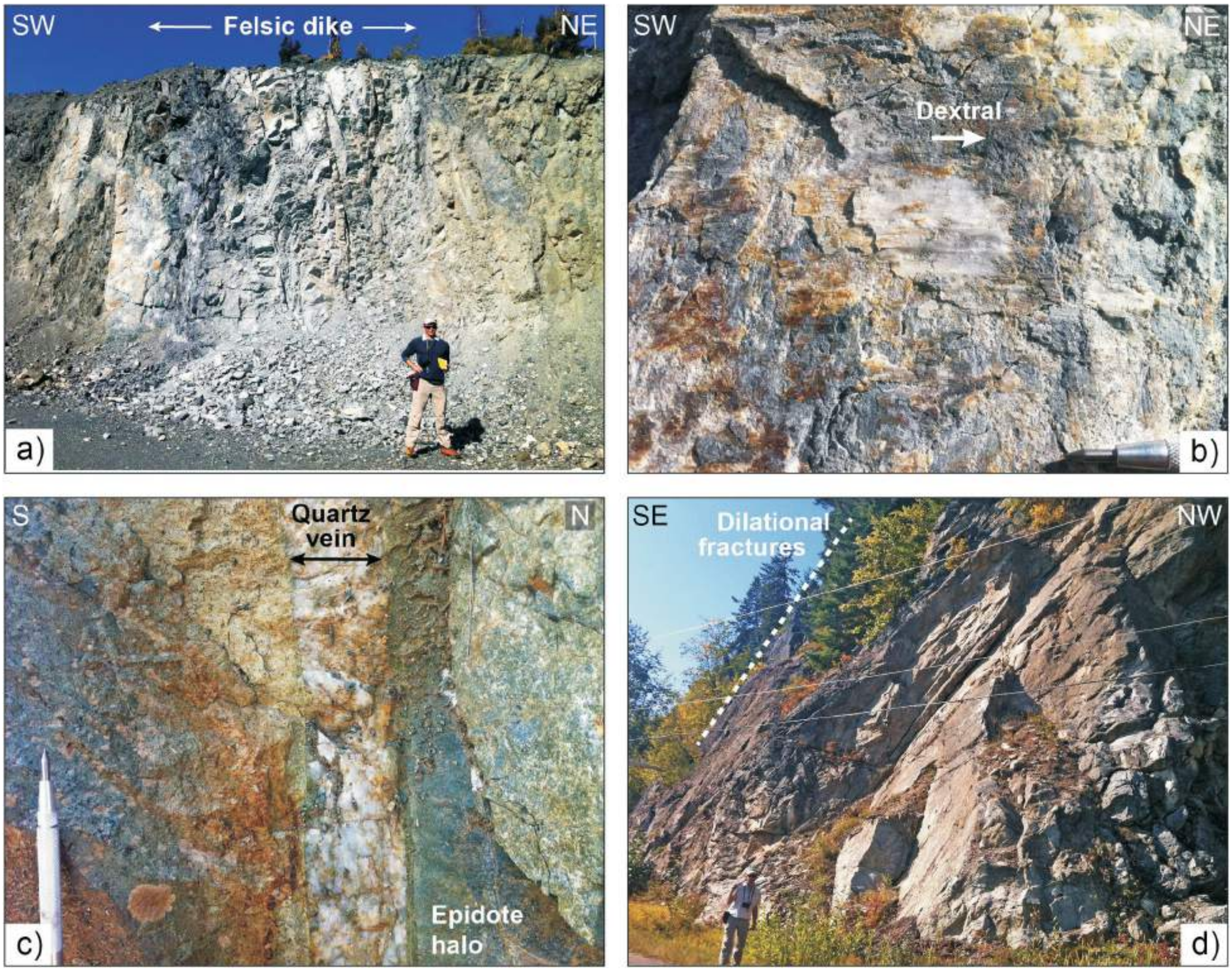

Figure 4. Northwest- and northeast-trending, steeply dipping brittle structures of the Eaglet Lake area: **a)** northwest-trending, plagioclase- and K-feldspar–phyric felsic dike intruding highly magnetic and nonfoliated basaltic rocks of the Slide Mountain Complex; **b)** northwest-trending, dextral strike-slip fault plane along the contact of felsic dikes and basaltic hostrocks; **c)** series of subparallel, northeast-trending, dilational quartz veins with epidote-chlorite haloes; **d)** subparallel, northeast-trending joints in granodiorite of Eocene age. Refer to Figure 3 for stereoplot graphics.

tion, this project will focus on the multi-dataset 'stacking' methodology (Sánchez et al., 2014). Deliverables will include

- an aeromagnetic-lineament map, including magnetite-destructive and magnetite-additive discontinuities;
- map of lineaments defining magnetic-anomaly axes;
- a multi-dataset attribute database, including airborne magnetic and gravity interpretation, and structural geomorphology for lineament reliability index; and
- airborne magnetic- and gravity-domain maps.

The goal is to generate an updated 1:400 000 scale geological map for the QUEST project area. This final phase of the project will consider

- multilayer correlation of airborne magnetic and gravity domains with known geological units; and
- interpretation of aeromagnetic lineaments as faults, sedimentary and metamorphic fabric, dikes or other geological structures.

All maps and digital files, including the new set of geophysical filters, will be delivered with the final technical report in April 2015. The goal is that this new geological and geophysical dataset will contribute considerably to a better understanding of BC's geology and can be used as a base layer for the exploration for porphyry-style deposits across the QUEST project area. Airborne magnetic surveys constitute one of the most widely used geophysical techniques for mineral exploration, and their structural interpretation has long been used as a guide to regional structural controls on mineralization. The outcomes of this study will enhance mineral exploration decision-making by providing the structural framework required for porphyry and related deposits. Both the structural setting for porphyry emplacement and the subsequent structural disruption may be elucidated.

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