

# High-grade hydrothermal copper-gold mineralization in foliated granitoids at the Minto mine, central Yukon

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## ABSTRACT

Speculation regarding the genetic history of the Minto copper-gold deposit in the Carmacks map area (NTS 1151) has existed since its discovery. Minto copper sulphides are hosted in sheet-like expanses of biotite-rich, variably deformed granitoids surrounded by massive granodiorite. Attempts to explain Minto's unusual mineralization style have ranged from digested red-bed copper, to aborted and deformed porphyry, and recently to an Iron Oxide Copper Gold (IOCG) type system. Although these commonly used genetic frameworks can explain many aspects of Minto-style mineralization, questions regarding chemistry, paragenesis, and structural controls on mineralization still remain. This paper is part of an M.Sc. thesis project that will focus on characterizing mineral textures, mineral chemistry, mineral paragenesis and micro and macro structural analyses to improve our understanding of the Minto copper-gold mineralized system and to enhance regional exploration potential in the district. This paper summarizes some preliminary observations at the Minto deposit and outlines future research.

## RÉSUMÉ

L'origine du gisement de cuivre-or de Minto, dans la région cartographique de Carmacks, a été le sujet de spéculations depuis sa découverte. À Minto, les sulphures de cuivre sont contenus dans des couches de granitoïdes riches en biotite et à déformation variable entourés de granodiorite massive. Ce style peu commun de la minéralisation fût au préalable expliqué par de nombreux modèles, incluant: 1) du cuivre sédimentaire digéré par l'intrusif; 2) un système de porphyre interrompu et déformé; ou 3) un système de type cuivre-or-oxide de fer (IOCG). Bien que ces divers modèles expliquent plusieurs des caractéristiques de la minéralisation à Minto, plusieurs questions demeurent à propos des contrôles chimiques, paragénétiques, et structuraux sur la minéralisation. Cet article fait parti d'un projet de maîtrise concentré sur les textures, la chimie, et la paragénèse des phases minérales, et sur l'analyse micro- et macro-structurale du système minéralisé en cuivre-or de Minto. Cette étude a pour bût d'améliorer notre connaissance du gisement de Minto et d'accroître le potentiel pour l'exploration du district. Cet article présente des observations préliminaires sur ce gisement et établi la direction de cette étude.

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## INTRODUCTION

The Minto mine (Yukon MINFILE 1151 021; Deklerk, 2008) consists of a series of high-grade Cu-Au deposits with a measured and indicated resource at 0.5% Cu cutoff of ~19.3 Mt averaging 1.42% Cu, 0.51 g/t Au and 5.38 g/t Ag, plus an additional inferred resource of ~15.1 Mt averaging 0.89% Cu, 0.25 g/t Au and 2.6 g/t Ag at the same cutoff (Sherwood Copper Corp., News Release #08-30, August 5, 2008). The deposit is hosted in the Granite Mountain batholith, approximately 240 km north of Whitehorse and 35 km southwest of Pelly Crossing in central Yukon (Figs. 1 and 2). The main Minto deposit was discovered in 1973 and was the subject of intermittent exploration in the 1970s, 1980s and 1990s. Mine development was initiated in the mid- to late 1990s by Minto Explorations Ltd. but was suspended in 1998 due to low metal prices. Sherwood Copper Corporation (now Capstone Mining Corporation) acquired 100% interest in the Minto project in 2005 and quickly resumed mine development. The Minto mine entered commercial production in October 2007.

Studies on the genesis of the Minto deposit were conducted at various stages in its exploration history. Sinclair (1977) interpreted the Minto deposit as a redbed copper deposit that was assimilated by the younger (Early Jurassic) Granite Mountain batholith. Pearson and Clark (1979) suggested that Minto resulted from metamorphism of a pre-existing hydrothermally derived copper-gold deposit hosted in rafts of Paleozoic Pelly Gneiss (now part of the Simpson Range plutonic suite; Colpron, 2006). More recently, Tafti (2005) concluded that the Minto deposit was an aborted or stalled porphyry system, although an Iron Oxide Copper Gold (IOCG) style of mineralization has not been ruled out (Tafti, 2005; Quin and Mercer, 2008).

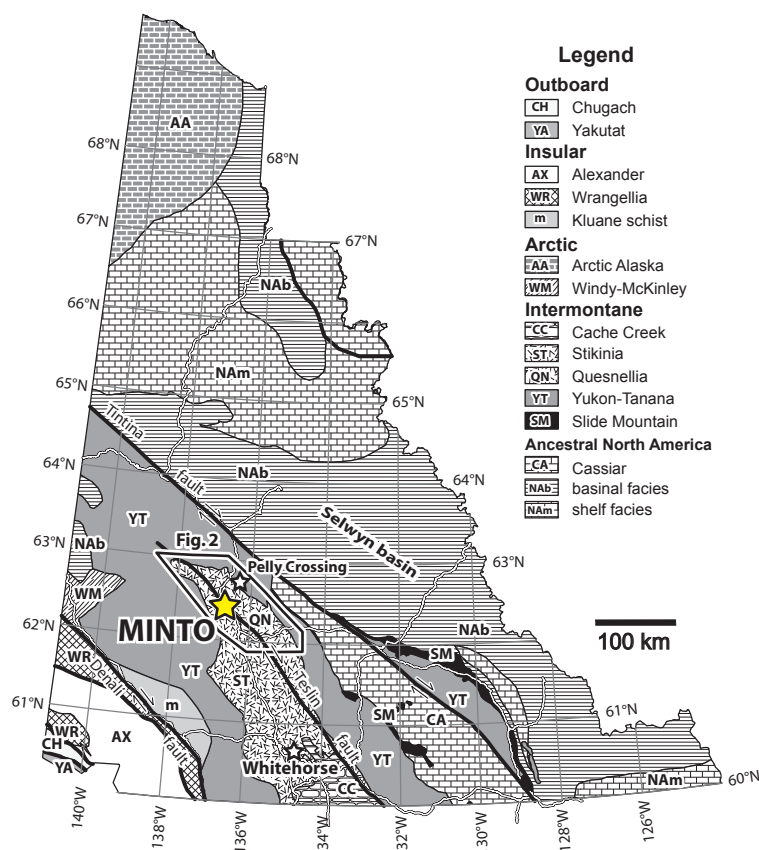
The goal of this study is to refine our understanding of the genesis and subsequent evolution of economic mineralization at Minto in light of the vast amount of geoscience data collected since 2005 through geological drill core logs, geochemical analyses, geophysical surveys, and ongoing open-pit extraction of the ore body. Specific objectives are:

(i) to determine the possible influence of pre-, syn- and post-mineralization structural controls on ore and grade distribution, including the development of a geometric and kinematic model for the structural development of the deposit;

(ii) to characterize the style and spatio-temporal distribution of alteration and mineralization at the Minto deposit, particularly mineral textures, mineral chemistry, mineral paragenesis and their relationships to structures; and

(iii) to develop an improved genetic model for the Minto deposit and clarify its relationship to other Cu-Au ore systems.

Initial fieldwork for an MSc study of the Minto deposits was conducted between June and August, 2008. The primary objectives for this first field season were to become familiar with the deposit features (lithologies, structure, sequence and variety of alteration) and to begin detailed logging of a series of drill core in order to define a down-dip transect of the deposits. Logging was performed on holes in Areas 2 and 118 (Fig. 3a). These detailed logs will provide the basis for interpreting the large database of existing drill logs, core photography and geochemical analyses maintained by Capstone Mining Corporation; these interpretations will determine property-scale



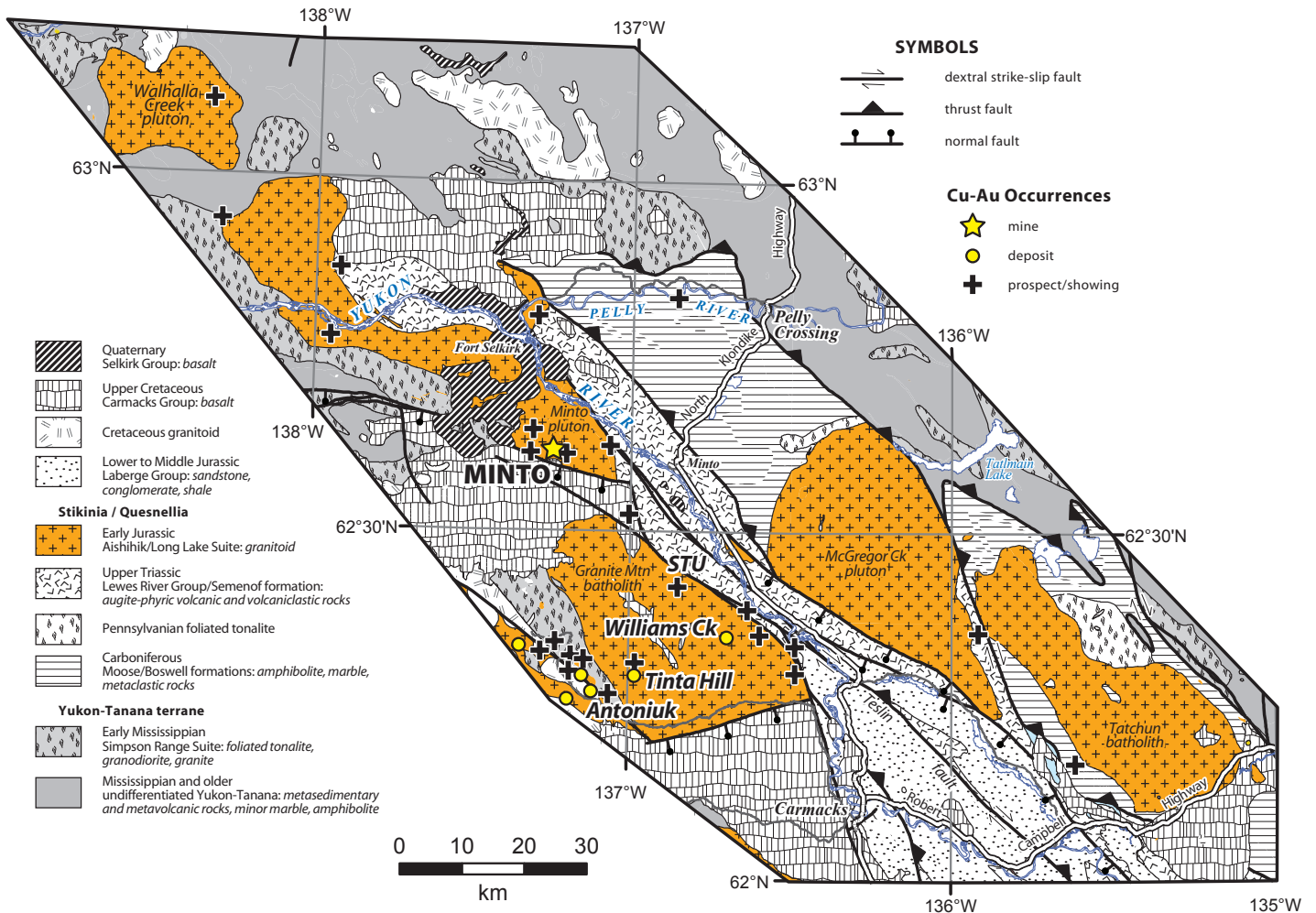
**Figure 1.** Terrane map of Yukon illustrating the location of the Minto mine. Parallelogram outlines location of Figure 2.

trends in mineralization, alteration and structure. The results of this study will assist in designing exploration strategies to facilitate discovery of additional Cu-Au deposits in the district. This project is a partnership between Capstone Mining Corporation, the Yukon Geological Survey, and the Mineral Deposit Research Unit (MDRU) at the University of British Columbia.

## PROPERTY GEOLOGY AND DEPOSIT CHARACTERISTICS

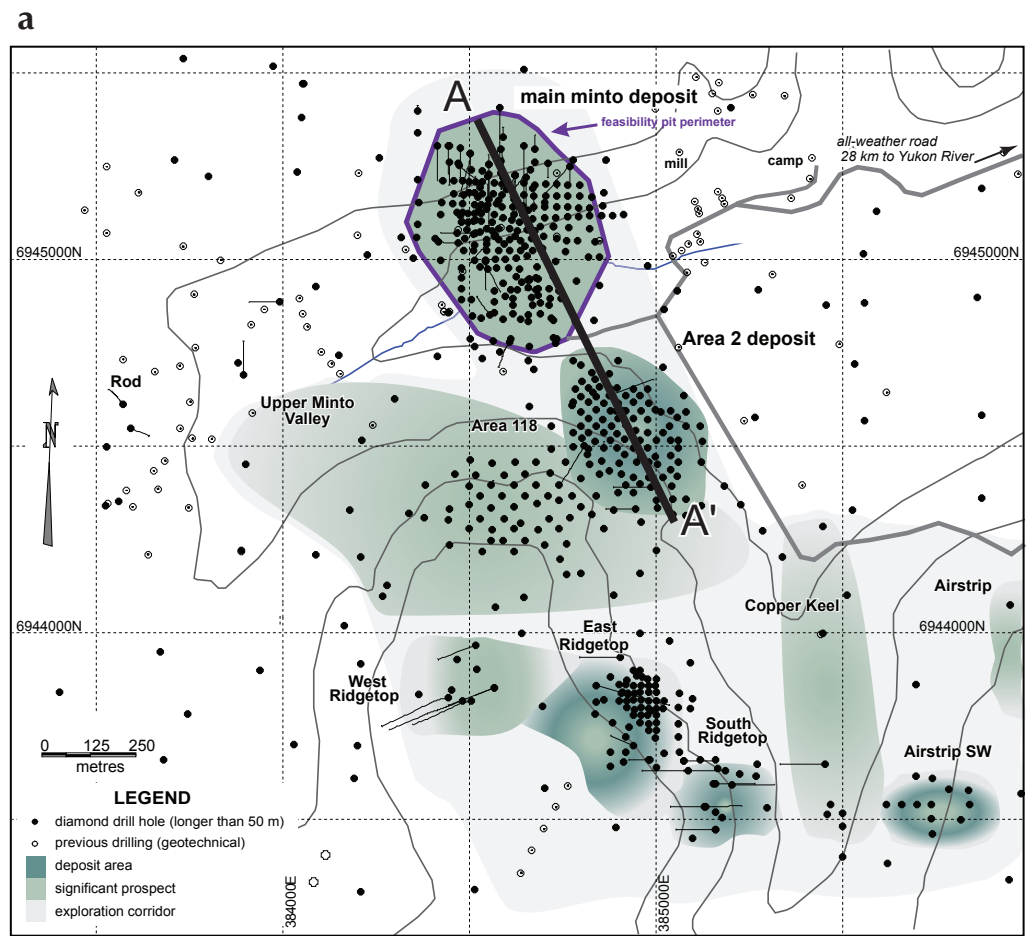
The Minto mine is located in the centre of Carmacks map area (NTS 1151) within the Carmacks copper belt of west-central Yukon. This mineralized belt is a 180 km by 60 km-wide belt of similar intrusion-hosted Cu-Au mineralization trending approximately north-northwest. This district also includes the Williams Creek (now Carmacks Copper) deposit (Yukon MINFILE 1151 008) and

the STU prospect (Yukon MINFILE 1151 011) to the southeast of Minto (Fig. 2). Regional 1:250 000-scale mapping of the area was first conducted by Bostock (1936) and subsequently updated by Tempelman-Kluit (1984). The Minto deposit is hosted in intermediate to felsic intrusive and meta-intrusive rocks of the Early Jurassic Granite Mountain batholith, specifically the Minto pluton, which intrudes the boundary between Stikinia and Yukon-Tanana terranes (Figs. 1 and 2; Tempelman-Kluit, 1984; Gordey and Makepeace, 1999; Colpron, 2006). The Minto pluton intrudes Upper Triassic augite-phyric basalts of Stikinia (or Quesnellia) to the east and north, and Early Mississippian meta-plutonic rocks of Yukon-Tanana terrane (Simpson Range plutonic suite) to the west (Fig. 2). Its eastern contact with Triassic rocks is locally faulted. To the south, the Minto pluton is in fault contact with basalt of the Upper Cretaceous Carmacks Group; further south, the Carmacks Group unconformably

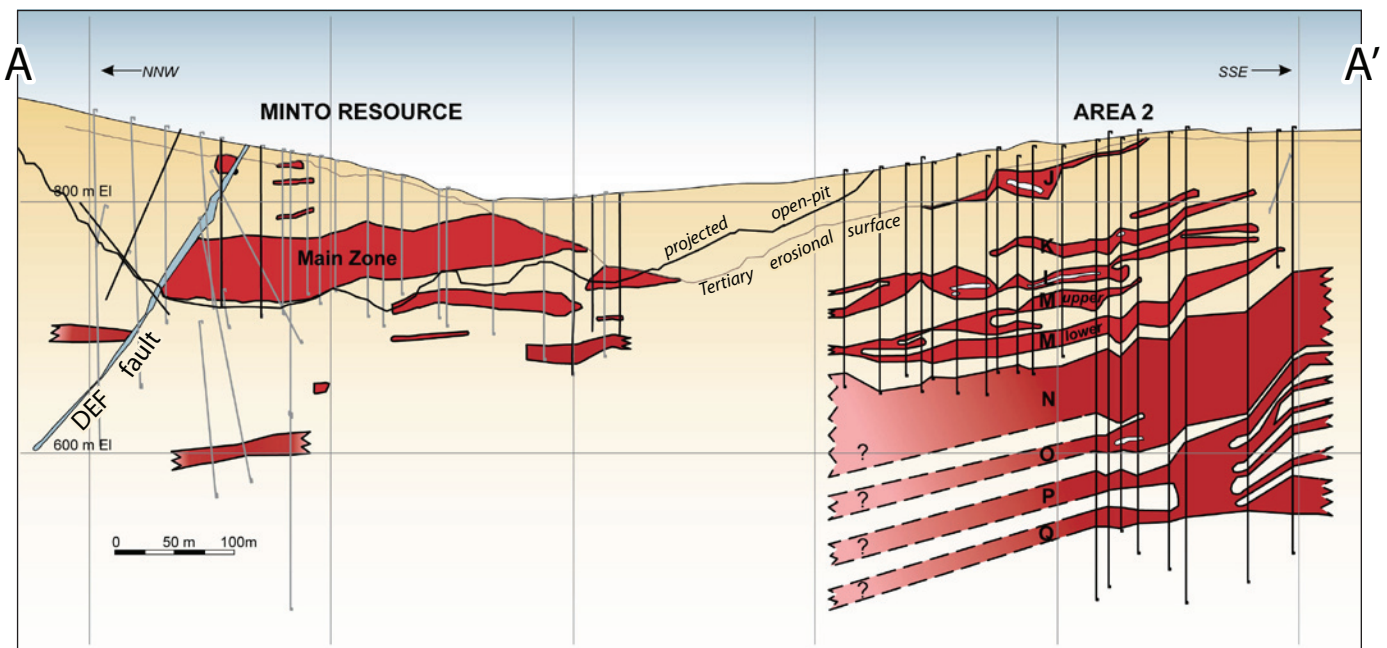


**Figure 2.** Regional geology of the Carmacks copper belt in west-central Yukon (modified from Tempelman-Kluit, 1984; Gordey and Makepeace, 1999; Colpron, 2006; and Colpron et al., 2007).

**Figure 3. (a)** Plan view of the Minto property illustrating the distribution of high-grade deposits and significant prospects (shaded areas). Coordinates NAD83, UTM Zone 8. **(b)** Cross-section A-A' from main Minto deposit to Area 2 depicting the stacked geometry of foliated and mineralized horizons (dark grey). Projected Minto pit outline is also shown. Section oriented 340° and located on Figure 3a.



**b**



overlies the southern portion of the Granite Mountain batholith (Fig. 2). North of the Minto property, Pliocene and younger basalt flows of the Selkirk Group cover the Early Jurassic intrusion.

The Minto pluton is dominantly composed of massive granodiorite (Le Bas and Streckeisen, 1991), but also includes sheets of variably deformed intrusive rocks (Fig. 3b). U-Pb zircon geochronology by Tafti (2005) indicates a maximum age of  $199 \pm 7$  Ma for the Minto pluton with younger phases ranging to  $\sim 185$  Ma. Geothermobarometric analyses suggest an emplacement depth of at least 9 km and crystallization temperatures of ca.  $711^\circ\text{C}$  for the youngest phase (Tafti, 2005). However, occurrences of magmatic epidote in older phases indicate that part of the Minto pluton crystallized at pressures in excess of 6 kbar (18-20 km depth; Tafti, 2005). In the southern portion of the Minto property, the pluton is unconformably overlain by a Late Cretaceous(?) conglomerate that locally contains mineralized clasts. Primary hypogene mineralization at Minto is hosted by variably foliated granodiorite and diorite, with gneissic rocks containing the highest grades. Supergene mineralization occurs proximal to near-surface extension of the primary mineralization and beneath the Cretaceous conglomerate.

The Minto property comprises several high-grade deposits (e.g., the Minto open-pit mine, Area 2, Area 118 and Ridgetop) plus several other significant prospects (e.g., Copper Keel, Copper Keel South, Airstrip, West Ridgetop and Upper Minto Valley) clustered within an area approximately  $4 \text{ km}^2$  and centred on Area 118, located about 400 m south of the current open pit (Fig. 3a). Ongoing exploration drilling has now established continuity between some deposits (e.g., Main, Area 2, Area 118 and Copper Keel). Results from drilling are progressively suggesting that the Minto mineralization represents a single, large copper-gold deposit where the currently outlined deposits and prospects are actually high-grade pockets within a much larger copper-gold system (Fig. 3a). Discontinuities between areas appear to be due to post-mineralization faulting. In addition to the large aerial extent of this system, deep drilling ( $\sim 300$ - $350$  m) within each of these zones consistently shows that this system comprises up to 13 individual deformed and mineralized horizons, stacked in a sub-horizontal, openly folded geometry (Fig. 3b). Although the mineralization is generally contained within these deformed zones, not all horizons exhibit ore grades; but all horizons yield some degree of copper-gold mineralization, from geochemically

anomalous to very high grade. Individual horizons range from 1 to 2 m thick, to over 60 m thick, and have typical drill intersections of 10 to 25 m for the best mineralized intervals. A lateral continuity of individual horizons of up to 1.5 km was observed in drill holes and justifies the use of this stacked succession of deformation zones as pseudo-stratigraphy (Fig. 3b). This model has proven successful in guiding exploration and has provided additional copper-gold mineralization targets at the Minto property.

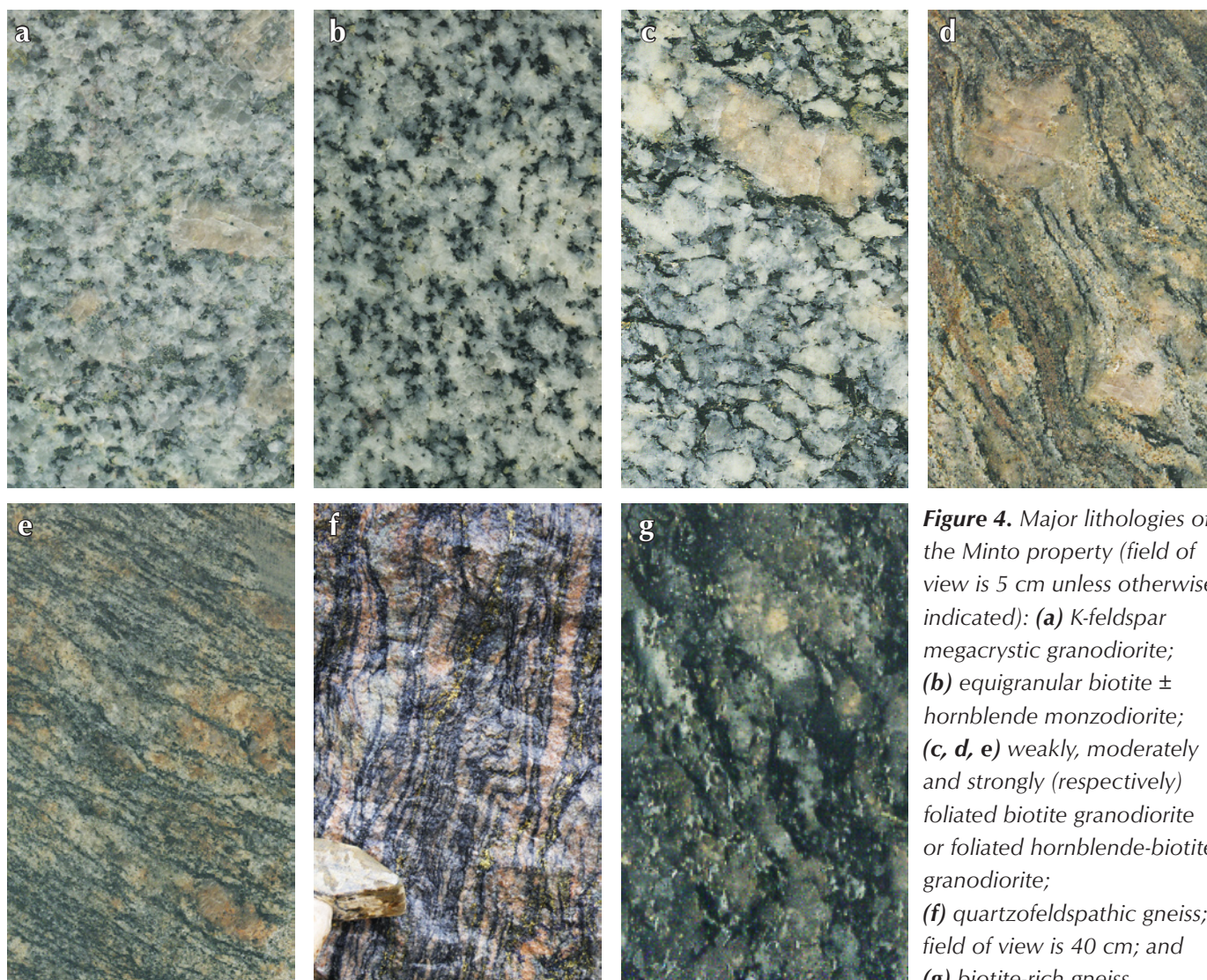
## MAJOR LITHOLOGICAL UNITS

Three major lithologies are identified on the Minto property and are differentiated by composition and degree of deformation. These rocks range from variably deformed gneisses to massive granitoids (Pearson, 1977; Tafti, 2005). Observations of lithological contacts were made mainly from drill core; preliminary interpretation of contact relationships will be discussed later in this paper.

### MEGACRYSTIC K-FELDSPAR GRANODIORITE

Composition of the megacrystic K-feldspar granodiorite unit (Fig. 4a) is predominantly granodiorite, but ranges to quartz diorite and rarely to quartz monzonite or granite. Plagioclase represents 50% of the modal mineralogy, K-feldspar 10-50%, quartz 20-25%, biotite  $\pm$  hornblende 10-15% and primary epidote  $<1\%$ . K-feldspar occurs as euhedral to subhedral phenocrysts, and commonly as megacrysts 1-8 cm long. Orientation of these megacrysts is nearly always random; weak local fabric development is ascribed to magmatic flow. Megacrystic K-feldspar granodiorite is observed within the Minto open-pit, and in places in drill core, it grades into equigranular biotite  $\pm$  hornblende monzodiorite (Fig. 4b). Composition and texture of this latter unit is nearly identical to the megacrystic K-feldspar granodiorite, but without potassium feldspar. Locally, glomeroporphyritic quartz ( $<1$  cm) is present in both the megacrystic K-feldspar granodiorite and equigranular biotite-hornblende monzodiorite.

The K-feldspar megacrystic granodiorite varies in texture from massive to foliated within the Minto pluton. Foliated biotite granodiorite and foliated hornblende-biotite granodiorite (Fig. 4c,d,e) contain plagioclase, quartz and potassium feldspar. Average modal composition is 40-45% plagioclase, 15-20% quartz, 10-15% K-feldspar, 10-15% biotite and 0-5% hornblende (substituting for biotite). Biotite, the dominant mafic mineral, defines a



**Figure 4.** Major lithologies of the Minto property (field of view is 5 cm unless otherwise indicated): (a) K-feldspar megacrystic granodiorite; (b) equigranular biotite  $\pm$  hornblende monzodiorite; (c, d, e) weakly, moderately and strongly (respectively) foliated biotite granodiorite or foliated hornblende-biotite granodiorite; (f) quartzofeldspathic gneiss; field of view is 40 cm; and (g) biotite-rich gneiss.

disjunctive and discontinuous foliation with centimetre-scale spacing. K-feldspar megacrysts are rotated, have common tails, and are fractured within these subunits. Red garnet is an uncommon accessory mineral and occurs locally as individual grains or as sub-millimetre-sized grains in 1 to 5 mm crystal aggregates.

### FOLDED QUARTZOFELDSPATHIC GNEISS

The folded quartzofeldspathic gneiss (Fig. 4f) consists of well developed, centimetre-thick compositional layers of mainly quartz and potassium feldspar, alternating with bands of biotite and magnetite. This unit contains 25-50% equigranular K-feldspar, 0-30% individual or layered bands of euhedral to subhedral magnetite, 25-30% equigranular quartz, 5-10% biotite and minor plagioclase. The compositional banding is nearly always folded by

centimetre to decimetre-scale disharmonic, gentle to isoclinal folds. Copper-sulphide mineralization in this unit is nearly ubiquitous and may represent up to 15% or more of the rock composition. Locally, magnetite-quartz gneiss contains up to 25% magnetite.

### BIOTITE-RICH GNEISS

The biotite-rich gneiss (Fig. 4g) is a major ore-hosting unit and is well exposed in the Minto main pit. Composition is commonly around 40-50% biotite, 30-40% plagioclase, and contains minor quartz and K-feldspar. Locally, this unit is composed of massive biotite.

## HYDROTHERMAL ALTERATION AND MINERALIZATION

Preliminary observations of alteration mineralogy and assemblages have been made through examination of drill core and the Minto pit. Assemblages listed here are grouped by their most commonly observed mineral associations.

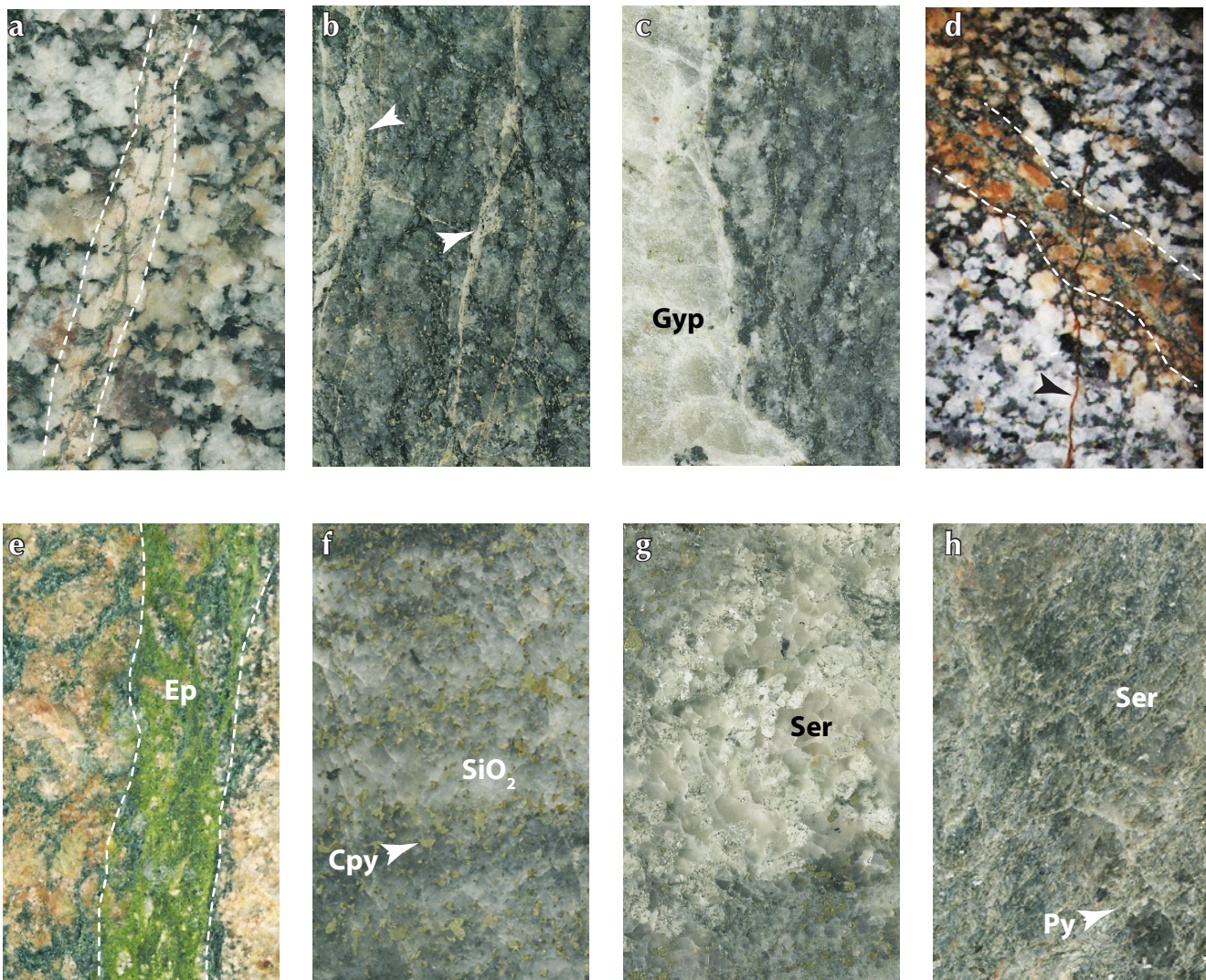
### VEINING

Veins are generally less than 0.5 cm in width and consist of late-stage calcite veining and fracture infill with

associated hematite veining (Fig. 5a); late-stage calcite veining and fracture infill without hematite veining (Fig. 5b); late-stage gypsum veining (Fig. 5c); late-stage hematite veinlets (Fig. 5d); and, epidote veins or stringers that are sharp-walled, without selvages (Fig. 5e).

### SILICIFICATION

A silica-rich alteration (Fig. 5f) commonly overprints the quartzofeldspathic gneiss, and in places overprints other lithologies and their alterations. In the silicified quartzofeldspathic gneiss, quartz forms the majority of



**Figure 5.** Common alteration assemblages of the Minto area (field of view is 5 cm unless otherwise indicated): (a) late-stage calcite veining (dashed outline) with associated hematite; field of view is 2 cm; (b) late-stage calcite veining (arrows); (c) late-stage gypsum (Gyp) veining; field of view is 2 cm; (d) late-stage hematite veining (arrow and dashed outline); field of view is 3 cm; (e) epidote (Ep) veining (dashed outline); field of view is 2 cm; (f) silicification ( $\text{SiO}_2$ ); note disseminated chalcopyrite [Cpy]; (g) sericite (Ser) pseudomorph of feldspar (saussuritization); (h) pervasive sericite (Ser) with pyrite (Py; arrow). [Figure 5 continues on next page.]

the rock matrix, and relict feldspar, sulphides and magnetite define a faint foliation.

### SERICITIZATION

Sericitization is observed in two forms at Minto. Most commonly, it is fine-grained saussuritization of plagioclase (Fig. 5g). Development of pervasive medium-grained white mica is less common (Fig. 5h). This alteration is texturally destructive and is associated with minor anhedral pyrite.

### EPIDOTE + CHLORITE ± MAGNETITE

The epidote + chlorite ± magnetite assemblage is characterized by the patchy replacement of biotite, hornblende and rarely K-feldspar by anhedral, patchy epidote (Fig. 5i). This secondary epidote is distinct from primary euhedral magmatic epidote locally observed in the granodiorite (Tafti, 2005). Biotite within the alteration

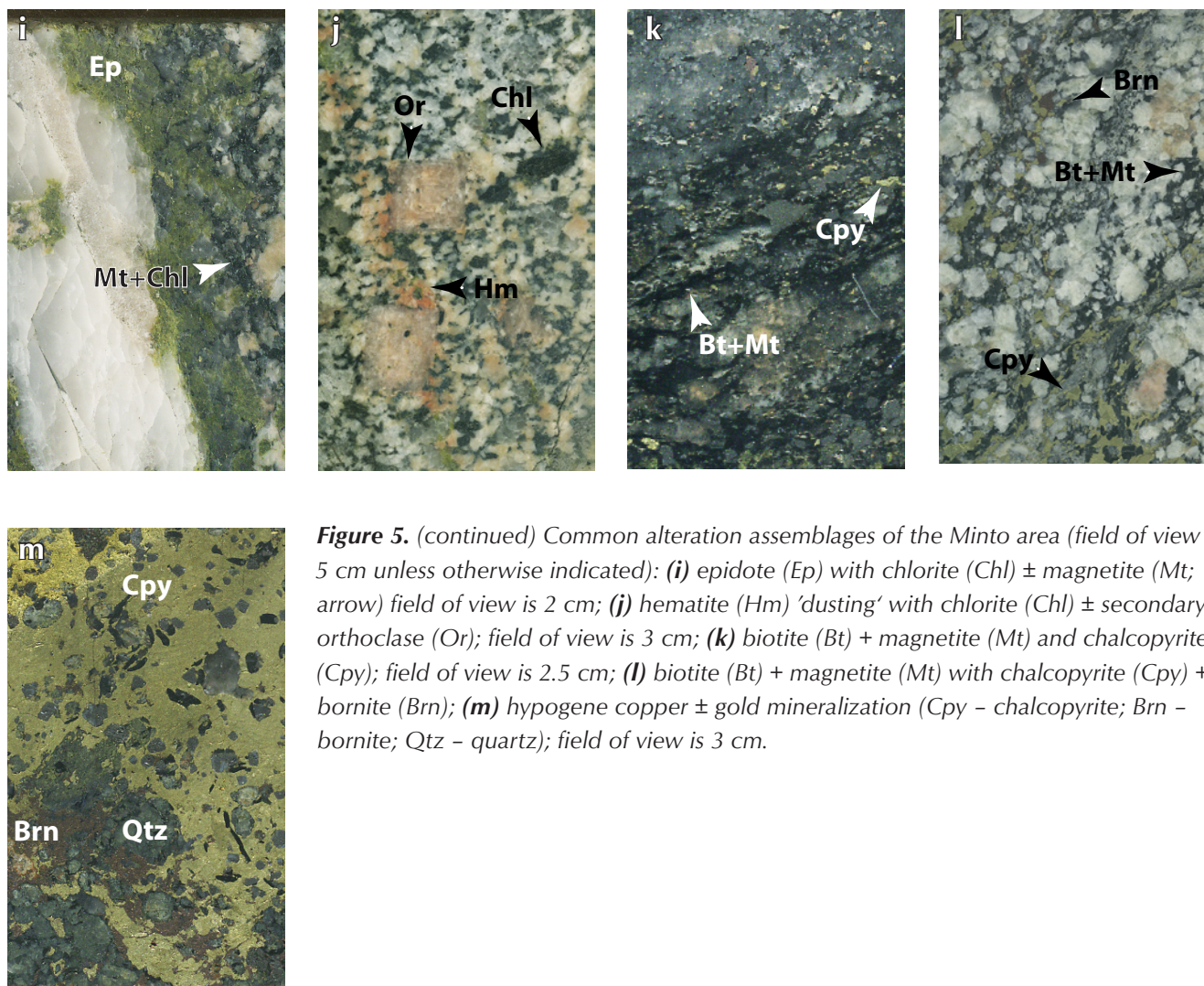
selvage is often weakly chloritized, and some zones contain alteration-associated magnetite.

### HEMATITE + CHLORITE ± K-FELDSPAR

Hematite + chlorite ± K-feldspar alteration is one of the most commonly observed alteration types within the Minto deposit. This alteration is characterized by pink fracture-controlled selvages of hematite dusting (Fig. 5j). This alteration is present in both deformed and undeformed units at Minto. It is rarely controlled by veinlets. Alteration selvages are millimetres to decimetres in scale. Feldspars are commonly replaced by orthoclase, and biotite and hornblende are generally replaced with chlorite.

### BIOTITE + MAGNETITE

Development of biotite and magnetite occurs in a range of lithologies and mineral associations, although always



**Figure 5.** (continued) Common alteration assemblages of the Minto area (field of view is 5 cm unless otherwise indicated): **(i)** epidote (Ep) with chlorite (Chl) ± magnetite (Mt; arrow) field of view is 2 cm; **(j)** hematite (Hm) 'dusting' with chlorite (Chl) ± secondary orthoclase (Or); field of view is 3 cm; **(k)** biotite (Bt) + magnetite (Mt) and chalcopyrite (Cpy); field of view is 2.5 cm; **(l)** biotite (Bt) + magnetite (Mt) with chalcopyrite (Cpy) + bornite (Brn); **(m)** hypogene copper ± gold mineralization (Cpy - chalcopyrite; Brn - bornite; Qtz - quartz); field of view is 3 cm.

within deformed units (Fig. 5k). Generally, this alteration appears to follow foliation, but is also seen as euhedral magnetite and biotite books within massive sulphides, or as massive shreddy biotite with magnetite.

## MINERALIZATION

Hypogene mineralization consists of chalcopyrite and bornite and very rare euhedral chalcocite; these minerals may occur in combination or as individual blebs of massive to semi-massive mineralization. Gold and silver occur as microscopic inclusions within bornite. Free native gold is rare. Mineralization is nearly ubiquitously contained within foliated rocks, although there is an isolated case of native copper enclosed in a K-feldspar megacryst within the massive K-feldspar granodiorite. Hypogene copper sulphidation may be part of the biotite + magnetite alteration assemblage, as biotite and magnetite nearly always occur together with chalcopyrite and bornite (Fig. 5l). Massive chalcopyrite and/or bornite occur as stringers in all deposits, but are most common in the Minto main pit (Fig. 5m). These stringers are observed as being both parallel and oblique to foliation, as well as cross-cutting the main foliation in ore horizons.

Supergene alteration at Minto has produced secondary copper minerals such as chalcocite, azurite and malachite. These minerals usually occur along rims or fractures of primary copper minerals, or as whole-grain replacement. Native copper is rarely present as narrow veinlets or isolated blebs. Zones of supergene alteration are commonly close to surface, and are only locally observed at depth due to fault-controlled meteoric water penetration.

## CONTACT RELATIONSHIPS BETWEEN LITHOLOGIES

Preliminary examinations of contact relationships at Minto were made during the Summer of 2008. The following observations are not definitive, and detailed work will be completed during the 2009 field season.

Based on macroscopic observations, contact relationships between deformed and massive units in the 2008 study areas are nearly always sharp, suggesting that they are intrusive in nature. However, a strain gradient over <1 cm is locally apparent in drill core, suggesting that some degree of deformation may be localized along the contacts. The foliation within the deformed horizons is nearly always parallel to the contacts with adjacent

massive units, a relationship that is most consistent with structural development of the contacts. However, after close examination of contact relationships in the main pit walls, the foliation was observed to be locally at high-angle to contacts with the massive unit, and may vary in attitude along the length of exposure. Microscopic examination of these contacts will be critical in determining their original nature and will help to determine the significance of deformation with respect to their development.

Preliminary analysis of lithological contact relationships with respect to foliation orientations within deformed horizons along a northwest-trending transect in the Area 2 deposit suggests a geometry of tight to isoclinal folding with a wavelength on the order of about 30 m. Folds within this area appear to trend approximately northwest, parallel to regional structural trends (Tempelman-Kluit, 1984). This suggests that some degree of deformation may predate emplacement of the massive units and that deformed lithologies are older than the massive units, an interpretation supported by isotopic age dates (Tafti, 2005).

## DISCUSSION AND FUTURE WORK

The purpose of the current study is to better understand the relationship of mineral chemistry, mineral paragenesis, and foliation development to fluid flow and metal precipitation in the Minto Cu-Au deposit. As discussed above, one fundamental issue at Minto is the relationship between massive and deformed units. What is the nature of lithological contacts: intrusive, flow-related, or tectonic? Do the foliated units have protoliths with similar bulk chemistry as the massive units? Or is their bulk chemistry similar to older units of Stikinia and/or Yukon-Tanana terrane that are intruded by the Granite Mountain batholith? What mechanisms have led to foliation development, and how are they related to regional tectonism?

Petrography, geochemistry, and micro and macro-structural examination will be used to establish the mineral paragenesis, structural and chemical evolution, and the fluid flow history at Minto. Relative timing between intrusion, deformation, and metasomatism and mineralization will be determined by field and laboratory observation of geologic relationships. Determination of post-intrusion (*i.e.*, metasomatic and metamorphic) mineral associations based on field observation and geochemical analysis will help to determine the alteration

paragenesis at Minto. Radiometric dating of molybdenite and other sulphide minerals by the  $^{187}\text{Re}/^{187}\text{Os}$  method will aid in constraining discrete mineralizing events within this paragenetic sequence. Subsequent comparison of grade, alteration, and mineral chemistry with a range of known hydrothermal Cu-Au deposits will allow for a better understanding of the Minto deposit relative to other Cu-Au systems on Earth.

## ACKNOWLEDGEMENTS

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