

Toward an Integrated Model for Alkalic Porphyry Copper Deposits in British Columbia (NTS 093A, N; 104G)¹

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INTRODUCTION

Recent discoveries have raised awareness of the economic importance of the alkalic class of porphyry and epithermal deposits, and have provided opportunities to better define the characteristics of these somewhat anomalous but potentially metal-rich mineral systems. Alkalic systems include some of the world's highest grade porphyry gold resources (e.g., Ridgeway, New South Wales, 53 Mt grading 2.5 g/t Au (4.26 million oz) and 0.77% Cu; Cadia Far East, New South Wales, 290 Mt grading 0.98 g/t Au (9.13 million oz) and 0.36% Cu), and some of the largest gold accumulations in epithermal settings (e.g., Lihir, Papua New Guinea, 44.7 million oz Au). Jensen and Barton (2000) have provided the most comprehensive review to date of alkalic mineral deposits (Fig 1), and descriptions of these deposits in British Columbia are available in Shroeter (1995).

Alkalic porphyry Cu deposits have features that distinguish them from the subalkalic porphyry systems. Although the alkalic porphyry deposits are known in various mineral provinces around the world, particularly in BC and eastern Australia, the quality of individual deposit descriptions in the public domain varies markedly. Thus, there are considerable gaps in knowledge regarding this important deposit type. Filling the knowledge gaps is the aim of a collaborative project between the Mineral Deposit Research Unit at the University of British Columbia, the Centre for Excellence in Ore Deposit Research at the University of Tasmania (Australia), Amarc Resources Ltd., AngloGold Ashanti Limited, Barrick Gold Corporation, Imperial Metals Corporation, Lysander Minerals Corporation, Newcrest Mining Limited, Newmont Mining Corporation, Novagold Resources Inc. and Teck Cominco Limited. Additional fi-

nancial support derives from grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Geoscience BC. This project seeks to build an integrated model for these deposits, including the characteristics of various alteration styles that can develop in either a shallow or deep-level alkalic igneous setting. This paper reports the early stages of the collaborative research on the alkalic porphyry deposits in BC.

British Columbia is the type area for alkalic porphyry deposits and is therefore the focus for any study of such systems. Furthermore, it is locally a data-rich environment with basic descriptions of many of the deposits (e.g., Schroeter, 1995) and detailed studies of a few (summarized in Lang *et al.*, 1995b). This project builds upon this database with new studies at the Mount Polley, Mount Milligan, Galore Creek and Lorraine deposits (Fig 2). The project also draws upon the recently published work on alkalic porphyry Cu-Au systems in New South Wales (e.g., Lickfold *et al.*, 2003; Wilson *et al.*, 2003; Cooke *et al.*, in press). Collectively, the new studies in BC were selected to span the apparent depth range of the porphyry systems, from high-level breccia-hosted bodies (Mount Polley) to deeper level intrusive-centred sulphide accumulations (Mount Milligan or Lorraine). In order to build a coherent model for alkalic porphyry systems, the integration of detailed structural, paragenetic, alteration zonation and geochemical information are essential. This paper presents a review of alkalic mineral deposits and preliminary results from the first year of a three-year study into the BC systems.

THE ALKALIC PORPHYRY ENVIRONMENT

Alkalic Au-Cu porphyry deposits are known in a few mineral provinces worldwide. The best known are from the Mesozoic arc of British Columbia and the Late Ordovician Lachlan Fold Belt of New South Wales (Australia). Other isolated alkalic systems include Dinkidi (Philippines) and Skouries (Greece). Alkalic porphyry deposits are locally high grade and associated with small-volume pipe-like intrusions that may have areal extents of only a few hundred square metres. They thus present difficult exploration targets. Furthermore, the alkalic porphyry systems lack advanced argillic alteration assemblages (possibly excluding Dinkidi), and there is no evidence of a connection to high sulphidization epithermal deposits, despite the local presence of high sulphidization alteration systems in New South Wales that are of the same general age as the alkalic porphyry deposits (Cooke *et al.*, in press). Phyllic alteration in the alkalic porphyry systems is typically restricted to fault zones that penetrate late in the hydrothermal system. Supergene enrichment zones will be, at best, poorly devel-

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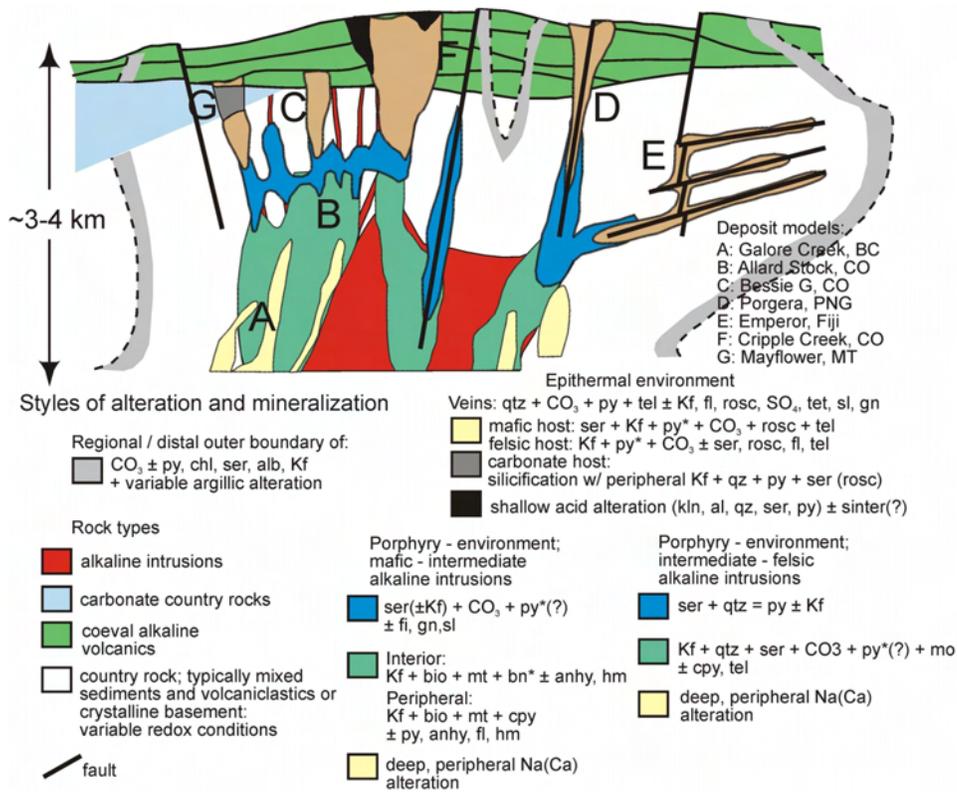


Figure 1. Schematic model of alkalic igneous complexes and associated ore deposit and alteration patterns (redrafted from Jensen and Barton, 2000).

oped due to the low sulphide contents of the alteration assemblages. The incipient nature of the peripheral hypogene alteration assemblages makes identifying the focus for fluid flow difficult when more than several hundred metres away from the mineralized centre. Skarns can occur in systems that contain carbonate hostrocks. Other manifestations of hydrothermal activity peripheral to alkalic

porphyry deposits are poorly documented and their exploration significance has not been assessed rigorously.

An empirical relationship has been postulated between alkalic epithermal and porphyry deposits, but it remains unproven (Jensen and Barton, 2000; Cooke *et al.*, in press; Fig 1). With the exception of Cowal in New South Wales (Australia), no significant alkalic epithermal deposits are known

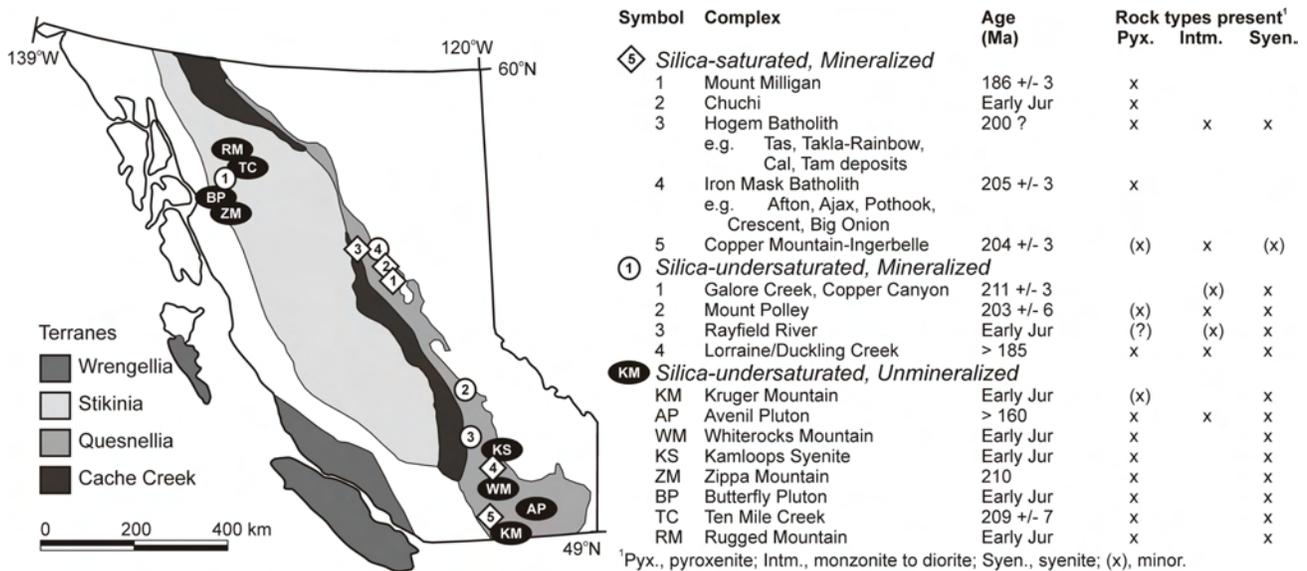


Figure 2. Location of early Mesozoic alkalic intrusive complexes and mineralized intrusions of British Columbia (Lang *et al.*, 1995a).

from the major alkalic porphyry belts of western New South Wales and British Columbia. One explanation for the negative relationship may be the depth of erosion, and hence a general lack of preservation of the shallower parts of alkalic magmatic-hydrothermal systems.

Alkalic Igneous Framework in British Columbia

Lang *et al.* (1995a) defined two suites of alkalic intrusions, silica saturated and silica undersaturated, associated with porphyry Cu-Au systems in British Columbia (Fig 2). Both suites are Triassic to Early Jurassic in age (Mortensen *et al.*, 1995) and represent the youngest intrusions in the Quesnel and Stikine terranes prior to the resumption of 'normal' calcalkaline arc volcanic rocks represented by the Early Jurassic Rossland Group and Ashcroft Formation in Quesnellia and the Hazelton Group in Stikinia. The alkalic deposits thus formed during a transition in the convergent margin evolution, a time that is thought to be conducive to the formation of porphyry Cu-type deposits (Tosdal, 2004).

The silica-undersaturated complexes are characterized by pyroxenite and syenite, and are locally zoned (Lueck and Russell, 1994). Potentially related volcanic rocks are only recognized in a few locations. The plutons have varying proportions of aegirine-augite, K-feldspar, biotite, melanite, titanite and apatite, with local hornblende, magnetite, plagioclase and vishnevitte-cancrinite. The accessory phase melanitic garnet (Ti-bearing andradite) is a distinguishing feature, and occurs as both a primary igneous phase and a hydrothermal alteration phase. Mineral chemical differences can distinguish the two paragenetic sequences (Lueck and Russell, 1994). Silica-saturated complexes, which are known only in Quesnellia, are dominated by diorite and monzonite. Pyroxenite and syenite are rare. Augite, biotite, magnetite, plagioclase, K-feldspar and apatite are the major mineral phases, whereas hornblende and titanite are less common. Quartz is rare.

Of the known major alkalic porphyry Cu-Au systems in BC (Copper Mountain, Chuchi, Ajax, Iron Mask, Mount Polley, Galore Creek, Copper Canyon, Mount Milligan, Red Chris; Fig 2), there are five mineralized centres associated with silica-saturated complexes and four with silica-undersaturated complexes (Lang *et al.*, 1995a). There are also other alkalic complexes that do not have known porphyry Cu-Au mineralized rock, and these are apparently indistinguishable, at first glance, from those that contain Cu-Au-bearing sulphide minerals. Lueck and Russell (1994) proposed that the presence or absence of hornblende and magnetite in silica-undersaturated rocks is a diagnostic feature of mineralized versus barren, respectively, silica-undersaturated igneous complexes. No criteria have been proposed to distinguish the productive from the barren silica-saturated complexes. Regardless of the overall composition of the alkalic systems, the gross-scale petrological similarity between barren and mineralized intrusive complexes is a very common feature of the high-level plutonic and volcanic environment, and one that has been the subject of numerous geological investigations over the years.

Considerable effort has been devoted to defining criteria to distinguish potentially mineralized from barren igneous complexes, but usually with limited success. However, within the calcalkaline environment, it has become evident,

although not universally proven, that certain element trends typify igneous complexes containing rock mineralized with precious and base metals (Kay *et al.*, 1999). The elemental characteristics are essentially some of the diagnostic features of island arc rocks of 'adakitic' compositions. These characteristics are: enrichment in Sr, Na and Eu; depletion in Y and heavy rare earth elements; $\text{SiO}_2 > 56 \text{ wt}\%$; $\text{Al}_2\text{O}_3 > 15 \text{ wt}\%$; $\text{Na}_2\text{O} > 3.5 \text{ wt}\%$; $\text{Sr} > 400 \text{ ppm}$; $\text{Y} < 18 \text{ ppm}$; $\text{Yb} > 1.9 \text{ ppm}$; $\text{La/Yb} \sim 20$; and $\text{Sr/Y} \sim 40$ (Drummond and Denfant, 1990). The enrichment of Na is not seen in many of the adakitic complexes associated with porphyry Cu systems. The recognition of an igneous chemical association of many porphyry Cu deposits in calcalkaline environments has occurred since the last serious research effort on the alkalic igneous complexes in BC (Lang *et al.*, 1995a), although recent work by Logan (2005) and Logan and Mihalynuk (2005a, b) has begun to evaluate the igneous complexes on a regional basis. Some constraints are offered by recent work in eastern Australia, where the porphyry Cu-Au deposits are associated with K-enriched ($\text{K/Na} > 1$) alkalic and shoshonitic complexes that show additional enrichment in large-ion lithophile elements, abundances of low-mantle-compatibility elements and marked depletions in Ti, Nb and Ta (Blevin, 2002; Holliday *et al.*, 2002).

ALKALIC PORPHYRY DEPOSITS IN BC: ARCHITECTURE, IGNEOUS GEOCHEMISTRY AND HYDROTHERMAL ALTERATION

In order to build a coherent model for alkalic porphyry systems, the integration of detailed geological architecture, paragenesis, alteration zonation and geochemical information is essential. A review of the initial results based on fieldwork and laboratory studies from the Mount Polley, Mount Milligan and Galore Creek alkalic Cu-Au porphyry deposits is presented herein; these studies build upon previous studies (*e.g.*, Enns *et al.*, 1995; Fraser *et al.*, 1995; Lang *et al.*, 1995; Sketchley *et al.*, 1995; DeLong, 1996; Logan and Mihalynuk, 2005a; Logan, 2005).

Mount Polley

The Mount Polley Cu-Au mining district in central British Columbia consists of at least six discrete porphyry Cu-Au-Ag deposits and prospects associated with monzonitic intrusions emplaced into the alkaline island arc rocks of the Quesnel Terrane (Fig 2). Located 56 km northeast of Williams Lake, the district consists of the Cariboo, Springer and Bell zones, which have been previously mined, and the Northeast zone, which is currently being developed. Other sulphide occurrences on the property are known but have yet to be mined. Overall, the various deposits and prospects constitute a reserve of 41 Mt of ore grading 0.44% Cu and 0.28 g/t Au, with varying amounts of Ag (Imperial Metals Corporation, 2006). The Northeast zone orebody, the focus of investigation here, contains 9.1 Mt of ore grading 0.88% Cu, 2.9 g/t Au and 6.4 g/t Ag, with approximately 80% of the ore hosted in breccia and the remainder hosted in pre-mineral, equigranular, nepheline-normative monzonite.

Differences in Cu/Au ratio, Ag content, Mo content, alteration, hostrock (breccia-hosted versus non-breccia-hosted ore) and intrusive texture, coupled with the north-

ward tilting of post-mineral Early Jurassic strata on the north, all suggest that the current outcrop at Mount Polley represents an oblique cross-section through a series of spatially related but slightly different porphyry-style deposits (Fraser *et al.*, 1995; Logan and Mihalynuk, 2005a) that potentially formed at different crustal depths (Panteleyev *et al.*, 1996). The Northeast zone is considered to reflect the shallowest structural level presently known, and thus potentially provides a link between deeper level porphyry and shallower levels in the upper crust typical of epithermal environments.

INTRUSIVE ROCK SEQUENCE

The Northeast zone contains breccia-hosted sulphide minerals that cut equigranular monzonite of the host Mount Polley intrusive complex. A complex series of intrusive rocks is associated with the breccia (Fig 3). Based on detailed core logging of a representative section through the Northeast zone (section 18; Fig 4), the intrusive phases are divided into three broad categories: pre-breccia intrusions, syn-mineral intrusions and post-mineral intrusions. Chalcopyrite, bornite and pyrite are the principal sulphide minerals that cement the breccias, although other silicate, carbonate and oxide phases and rock-flour matrix locally form infill to breccia clasts.

An equigranular monzonite forms the most volumetrically significant member of the Mount Polley intrusive complex, is the dominant clast type of the breccia, and represents the major pre-breccia intrusive unit in the Northeast zone. It is equigranular and fine to medium grained, with less than 10% mafic minerals. Potassium-feldspar (~70%) and plagioclase (~20%) are the dominant minerals. Internal to the body, fine-grained margins, inferred to represent chilled contacts, (*i.e.*, equigranular monzonite chilled against equigranular monzonite), suggest that this unit is not a single intrusive body but rather a swarm of coalesced dikes or stocks. The pre-mineral equigranular monzonite hosts xenoliths ranging from diorite to monzodiorite (Fig 5a), and of the host marine mafic volcanic rocks.

Megacrystic K-feldspar-phyric monzonite porphyry represents the volumetrically most important syn-mineral and syn-breccia intrusions. Within the deposit, the megacrystic monzonite porphyry is present as breccia clasts. Outside the breccia body, the megacrystic porphyry is present as discrete dikes intruding the host pre-mineral equigranular monzonite. Within the breccia, many megacrystic monzonite porphyry clasts have distinct fluidal shapes, suggesting a close timing of intrusion and brecciation (Fig 5b). More commonly, clasts are rounded to angular. Abundance of megacrystic porphyry clasts varies from absent to as much as 60 to 70% of the breccia. Diagnostic K-feldspar phenocrysts, which vary from 0.5 to 2 cm in length, form 20 to 30% of the porphyry. The phenocrysts are set in a fine-grained to aphanitic groundmass consisting of subequal plagioclase and K-feldspar. Mafic minerals, dominantly hornblende, form less than 5% of the rock.

Equigranular augite monzonite forms a second, volumetrically less abundant syn-mineral dike suite. This monzonite intrudes the mineralized breccia (Fig 5c) and is

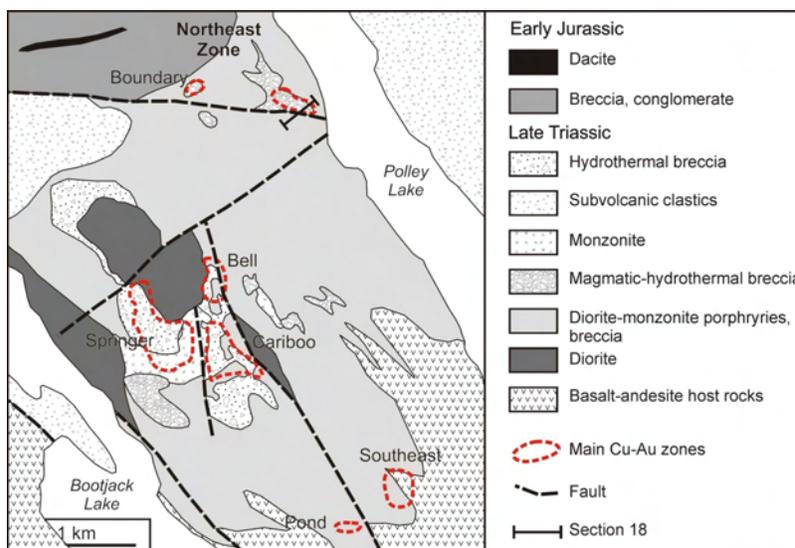


Figure 3. Simplified geology and location of mineralized zones at Mount Polley (Rees *et al.*, 2005).

locally cut by narrow (<1 mm) veins of chalcopyrite, bornite and magnetite that cross the contact into the host mineralized breccia. These relationships indicate that the equigranular monzonite intruded after brecciation but prior to a younger but less intense and spatially more restricted stage of sulphide mineralization.

Post-mineral dikes are compositionally and texturally distinct. They intrude mineralized breccia and late mineralized but post-breccia equigranular augite monzonite. Based on crosscutting intrusive relations, as well as mineralogy and inferred composition, the post-mineral dikes are divided into five families. These are, in order of decreasing age: K-feldspar-phyric monzonite porphyry (Fig 5d), K-feldspar and plagioclase-phyric monzonite porphyry, hornblende and biotite equigranular monzonite, plagioclase-phyric microporphyry, and mafic dikes. Among the post-mineral K-feldspar-phyric dikes, there is a general trend characterized by decreasing phenocryst size and abundance with time: the older dikes of the family contain up to 30% K-feldspar phenocrysts 2 to 5 mm in size, whereas the youngest have <5% K-feldspar phenocrysts 1 to 3 mm in size.

HYDROTHERMAL PARAGENESIS AND MINERAL CHEMISTRY

Sulphide minerals in the Northeast zone are principally cement to breccia clasts with less common replacement of rock-flour matrix or veins cutting clasts. Pyrite, chalcopyrite and bornite dominate, with trace amounts of galena and primary chalcocite (Fig 6a, b). Secondary covellite is also present. Chalcopyrite and bornite form a core to the orebody (Fig 7), and are surrounded by chalcopyrite and finally chalcopyrite accompanied by increasing pyrite towards the margins. As illustrated in Figure 7, based on a cross-section through section 18 (geology shown in Fig 4), the bornite and chalcopyrite zone is up to 30 m wide, the chalcopyrite zone is up to 150 m wide and the pyritic halo is at least 300 m wide. In the high-grade core, bornite frequently forms millimetre-scale rims on chalcopyrite.

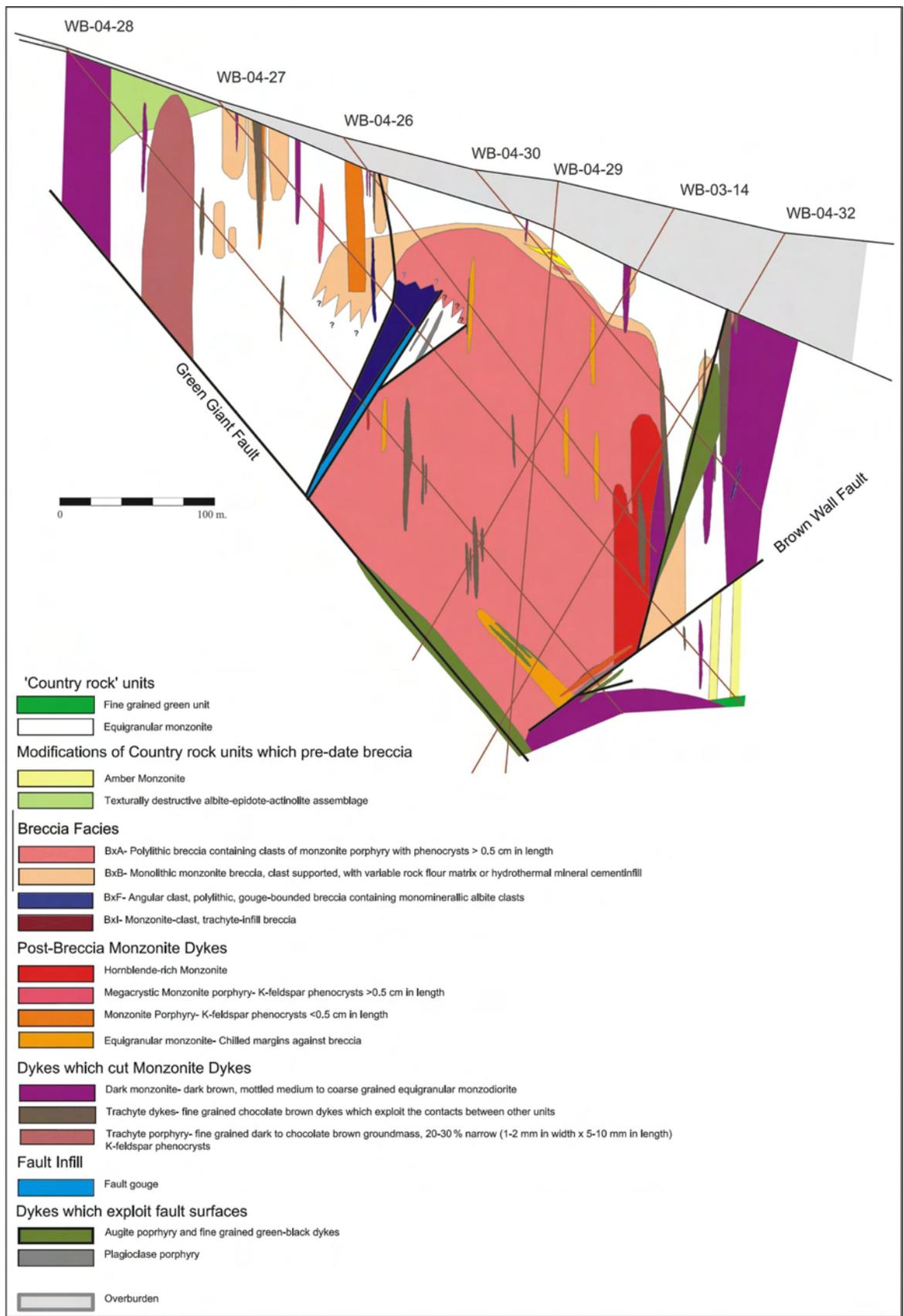


Figure 4. Cross-section along section 18, showing distribution of igneous rocks and breccia in the Northeast zone, Mount Polley.

Trace element chemistry shows that bornite and galena are elevated in Ag, whereas magnetite is elevated in Zn. Gold was not identified in any abundance in any sulphide minerals analyzed. Chalcopyrite is characterized by a trace element zonation, with Se and Bi elevated in the core of section 18 and decreasing in concentration outward. Deyell and Tosdal (2005, augmented in this study) showed that $\delta^{34}\text{S}_{\text{CDT}}$ values in chalcopyrite, pyrite and bornite range from -0.55 to -7.10% . The most negative sulphide values are from pyrite near the core of the deposit, but also near the top of the deposit and farther outboard from the core of the deposit (Fig 7). Both sulphide and sulphate $\delta^{34}\text{S}_{\text{CDT}}$ values are consistent with an oxidizing fluid source. At least two stages of early carbonate, one main stage, and multiple stages of late carbonate and anhydrite veins are also present (Fig 6c).

Mount Milligan

Mount Milligan, located 155 km northwest of Prince George, is the youngest alkalic-type porphyry Cu-Au deposit in BC. Total resources, as reported by Placer Dome Inc. (December 31, 2005), are 205.9 Mt grading 0.6 g/t Au (3.7 million oz) and 0.247% Cu (1.12 billion lbs).

The Mount Milligan area is moderately to steeply tilted (dipping $\sim 45^\circ\text{W}$), based on the dip of the host sequences as well as the geometry of the stocks and derivative sills, specifically the MBX stock and Rainbow dike (Fig 8, 9). Implicit in this geometry is that the bottom of each vertical drillhole has a more peripheral location relative to the stock than the top, so that outward gradational and zonal changes in alteration for a particular hole occur at depth. Consequently, due to the present structural orientation of the

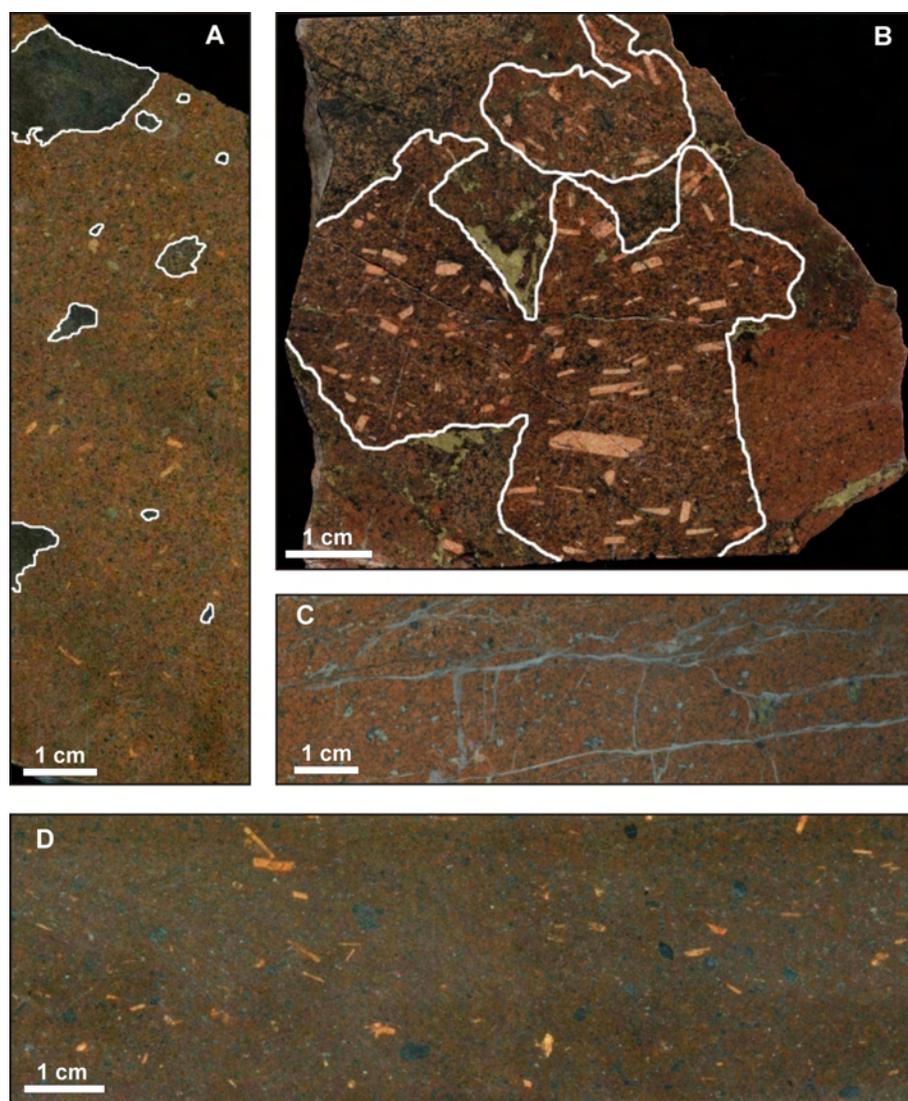


Figure 5. Representative intrusive rock in the Northeast zone of Mount Polley: A) pre-mineral equigranular monzonite; B) fluidal clast of megacrystic K-feldspar-phyric monzonite porphyry that is syn-breccia and syn-mineral; C) late syn-mineral equigranular monzonite; and D) post-mineral K-feldspar-phyric monzonite.

orebody, there is the opportunity to simultaneously track lateral and vertical physicochemical changes within the deposit. In addition, a fault separates a Au-rich but Cu-poor zone of the deposit (66 zone) from the Cu-enriched part of the deposit (MBX zone). Accordingly, the down-faulted segment preserves a part of the hydrothermal system that has been eroded elsewhere in the deposit, and provides a glimpse of the upper parts of the hydrothermal system. As a result, Mount Milligan provides a unique opportunity to define the lateral and vertical characteristics of mineralization and alteration, and broad-scale geochemical zonation with

respect to the regional architecture, building upon the previous work presented in Sketchley *et al.* (1995). Current research at this site is focused on defining the paragenesis of the deposit through a detailed examination of alteration, sulphide mineral distribution and broad-scale geochemical zonation with respect to the regional architecture.

In order to constrain the lateral and vertical changes in alteration and mineralization, a hinged cross-section (Fig 9) through the MBX stock and then southeast through the 'MBX' (Cu and Au-rich) and '66' (Cu-poor, Au-rich) zones was relogged. This section crosses the Rainbow

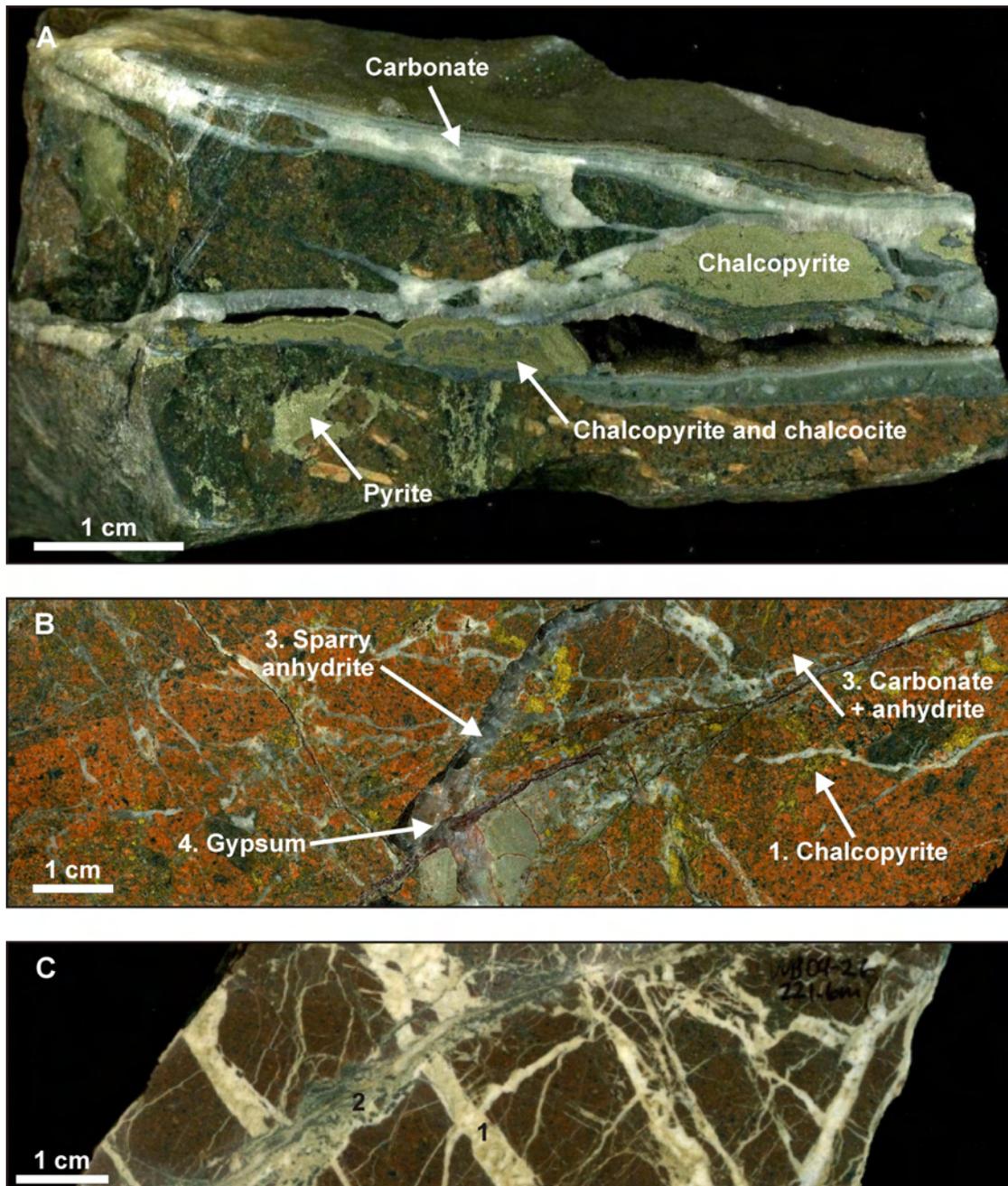


Figure 6. Examples of mineralized rocks in the Northeast zone of Mount Polley: A) main-stage Cu-sulphide mineralization and associated carbonate veins; B) chalcopyrite cut by late-stage carbonate, anhydrite and gypsum; and C) post-sulphide carbonate veins (1), in turn cut by younger carbonate veins (2).

fault, which is currently mapped with a northeasterly trend extending from the Divide fault to the Great Eastern fault, so that it truncates the Rainbow dike at its southernmost extent and separates the MBX and 66 zones. Formerly, the Rainbow fault was mapped as running north-south, parallel to bedding along the east side the Rainbow dike (Sketchley *et al.*, 1995). The revised fault geometry is significant because it implies that the transition in alteration and mineralization from the MBX to the 66 zone is not continuous. Furthermore, it is apparent that the moderately south-dipping fault has juxtaposed two different parts of the hydrothermal system. Accordingly, alteration and vein stages from the upper segments of 66-zone drillholes on the hangingwall of the Rainbow fault represent a portion of the deposit that has been eroded from the footwall.

HYDROTHERMAL ALTERATION ZONATION

By comparing the distribution of sulphide and alteration minerals sequentially from the stock outward, a generalized zone of strong potassic alteration (secondary orthoclase and biotite) between the MBX stock and the Rainbow dike (along the hangingwall of the dike) is interpreted to be the result of focusing of hot, magmatic-hydrothermal fluids. Lower temperature, propylitic alteration (chlorite-epidote-calcite-albite) typically occurs below the

footwall of the monzonitic Rainbow dike where it overprints potassic alteration in volcanic hostrocks. The propylitic zone becomes shallower with distance away from the stock, suggesting an upward, concentrically zoned pattern to the alteration zones.

Bedded volcanic units with high permeability are strongly potassically altered, suggesting some lateral channellizing of high-temperature magmatic fluids. The net effect of the channellized flow is propylitically altered rocks, representative of lower temperature fluids or the interaction of orthomagmatic and meteoric fluids, sandwiched between zones of strong potassic alteration near the monzonite intrusion, and in high permeability rocks at depth (180–200 m). Overall, the alteration pattern reveals more complexity to the fluid flow than implied by the gross-scale concentric alteration pattern. Clearly, structure and lithology are major contributing factors defining the deposit paragenesis, as well as the distribution of alteration assemblages.

Mineral mapping using a short-wave infrared (SWIR) instrument demonstrates that an approximately 100 m wide potassic zone adjacent to the stock is surrounded by an approximately 60 m wide sodic-calcic zone, which grades upward into a chlorite-sericite assemblage. Late-stage alteration (illite-montmorillonite-sericite) is superposed on the

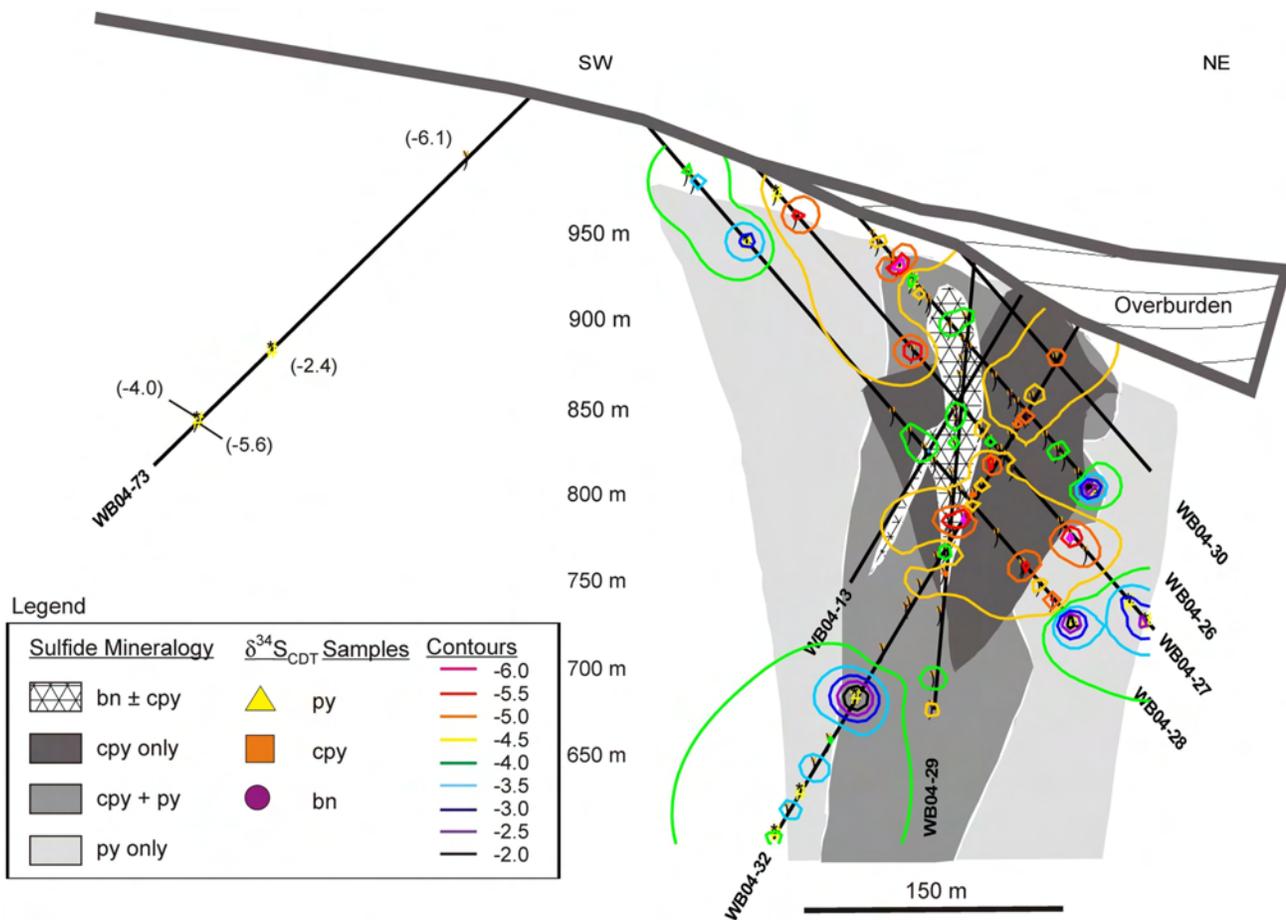


Figure 7. Distribution of sulphide minerals and contoured sulphur isotope ($\delta^{34}\text{S}_{\text{CDT}}$) data across section 18. Contours are based on results from all sulphide minerals of Deyell and Tosdal (2005), supplemented by new data. $\delta^{34}\text{S}_{\text{CDT}}$ samples with numbers in brackets have been provided for completeness; these values were not included in contours. Sulphide mineralogy from Deyell and Tosdal (2005). Abbreviations: bn, bornite; cpy, chalcocopyrite; py, pyrite.

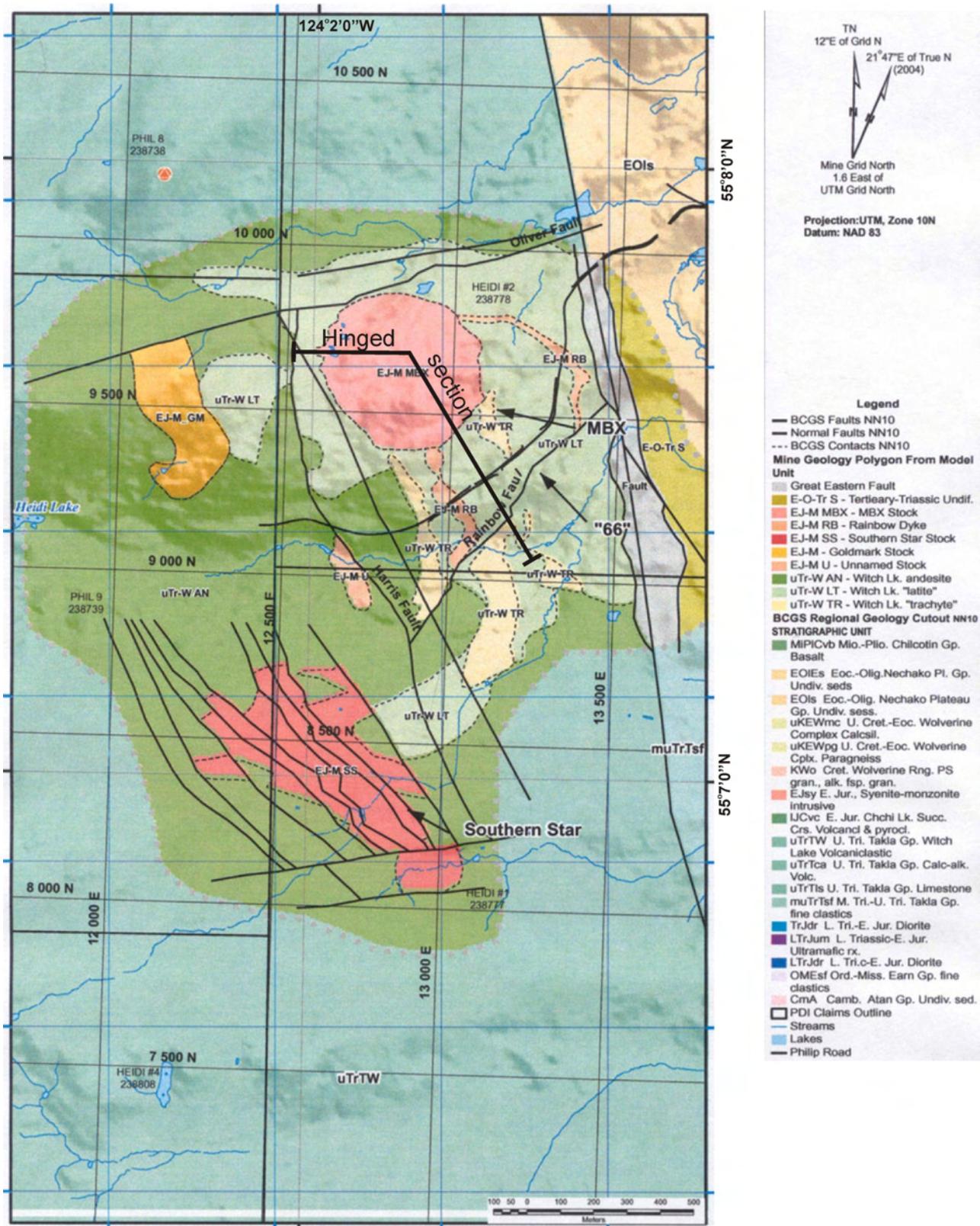


Figure 8. Location and simplified geology of Mount Milligan deposit.

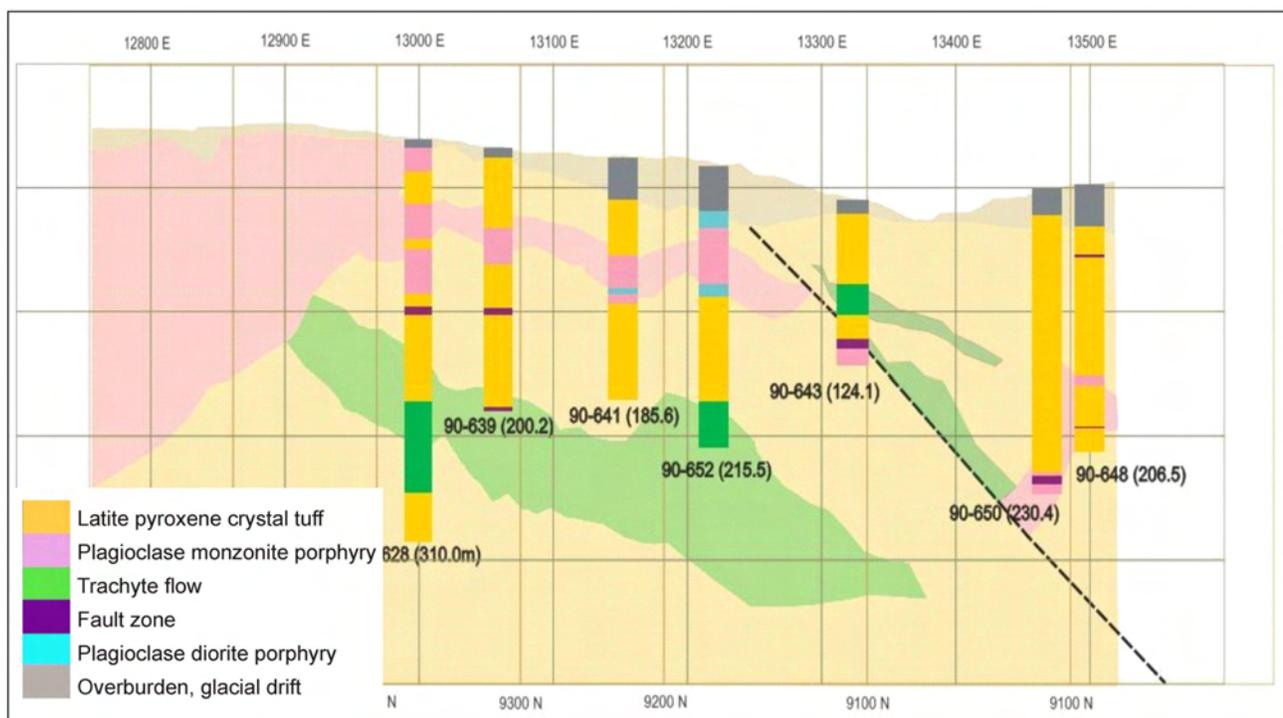


Figure 9. Compiled cross-section of the Mount Milligan deposit; see Figure 8 for location.

potassic zone and along the Rainbow dike, suggesting prolonged fluid channelization due to higher permeability and/or hostrock fracturing.

Analysis of $\delta^{34}\text{S}_{\text{CDT}}$ values in association with the sulphide from which they were obtained was undertaken to determine if $\delta^{34}\text{S}_{\text{CDT}}$ values correlated with particular mineralization events, such as early versus late veins, and disseminated sulphide minerals (Fig 10). There appears to be a distinct difference between Au-deficient, late pyrite-magnetite-chlorite veins/clots ($\delta^{34}\text{S}_{\text{CDT}}$ values ranging from -1 to 0%) and sulphide minerals from earlier veins and disseminations. Although, differences in $\delta^{34}\text{S}_{\text{CDT}}$ values among earlier sulphidization events are unclear, there may be a difference between potassic and propylitic sulphide events, with early veins (most with a chalcopyrite component) and disseminations having $\delta^{34}\text{S}_{\text{CDT}}$ values between -3 and -2% , and pyrite veins with propylitic halos and lesser chalcopyrite ranging between -2.2 and -1.5% . In terms of metal concentrations, near-zero $\delta^{34}\text{S}$ values are Au-Cu deficient. The range of $\text{Cu}/\delta^{34}\text{S}$ ratios is widest near the MBX stock and generally decreases with distance. The same pattern is observed with $\text{Au}/\delta^{34}\text{S}$ ratios, although there is a jump in Au values and $\text{Au}/\delta^{34}\text{S}$, potentially indicating a second mineralization event involving Au transported as a bisulphide versus chloride complex. Generally, there appear to be at least three phases of mineralization with distinct ranges of $\delta^{34}\text{S}$ values.

Galore Creek

Galore Creek is the most important example of the silica-undersaturated class of alkalic porphyry Cu-Au deposits (Lang *et al.*, 1995). The property is underlain mainly by marine volcanic and sedimentary rocks of the Middle to

Upper Triassic Stuhini Group (Fig 11). These rocks are intruded by an alkali syenite complex composed of multiple intrusions emplaced into volcanic rocks of similar composition. To date, 12 Au-Ag-Cu mineralized zones have been identified (Fig 12). Overall, the mineralized zones extend more than 5 km in length and 2 km in width. The mineralization is hosted predominantly in highly altered volcanic rocks and, to a lesser degree, in syenite intrusions. The largest zone of mineralization, the Central zone, and the flanking North and South gold zones, host high-grade Cu-Au, have marked spatial variation in Au/Cu ratio, and are unique among the alkalic porphyry Cu-Au deposits in the high abundance of garnet within the alteration parageneses (Enns *et al.*, 1995). The temporal and spatial evolution of hydrothermal fluids in this deposit is therefore of interest in elucidating the characteristics that governed the formation of the deposit.

HYDROTHERMAL ALTERATION ZONATION PATTERNS

Five broad styles of alteration are manifested as alteration assemblages at Galore Creek, and are summarized in Figure 13.

Calcsilicate Alteration

A calcsilicate assemblage dominated by diopside and pale brown garnet replaces one or more fragmental horizons in the footwall of the pre-mineralization porphyry stock. This assemblage is considered to constitute prograde skarn and is metal poor unless overprinted by hydrothermal biotite. In the Central zone, crosscutting relationships with the K-silicate assemblage and lack of mineralization indicate that this alteration is early in the sequence.

Potassium-Silicate Alteration

Potassium-silicate alteration dominates and affects the host volcanic rocks, pre and syn-mineral porphyries and, to a minor extent, post-mineral porphyries (see Enns *et al.* (1995) for a thorough review of the intrusive history). The

most intense K-silicate alteration in pre-mineral porphyry consists of K-feldspar, biotite, magnetite and anhydrite, with associated bornite and chalcopyrite. Potassium-silicate alteration is notably weaker in syn-mineral porphyry, although biotitization of a rock-flour matrix breccia is locally intense.

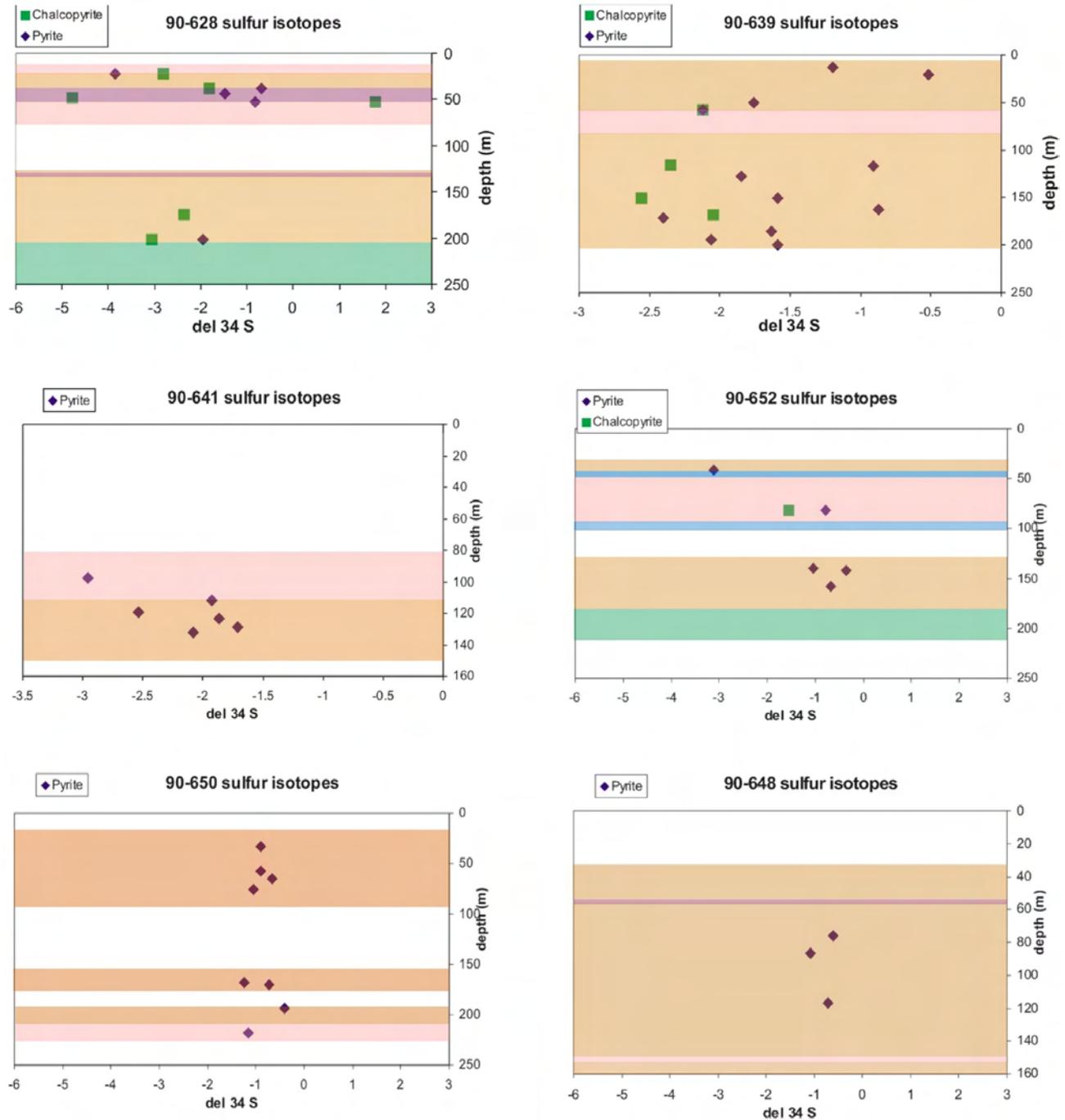


Figure 10. Sulphur isotope ($\delta^{34}\text{S}$) values versus depth and lithology for the six Mount Milligan drillholes sampled (Jago, 2006). Legend: blue diamonds, pyrite; green squares, chalcopyrite; pink shading, Rainbow dike (or MBX Main stock at ~20 m depth in 90-628); brown shading, 'latite'; green shading, 'trachyte'; purple shading, fault zone; blue shading, monzodiorite porphyry dike (suggesting that the Rainbow dike is a potassically altered monzodiorite dike versus a true 'monzonite'). Note the decrease in the range of values outward from the centre of the system, and the overall shift to near-zero values. The widest range of values in 90-628 is situated within the faulted rock on the hangingwall of the Rainbow Dike, indicating prolonged fluid channelization.

Figure 11. Simplified geology of the Galore region (adapted from Enns et al., 1995).

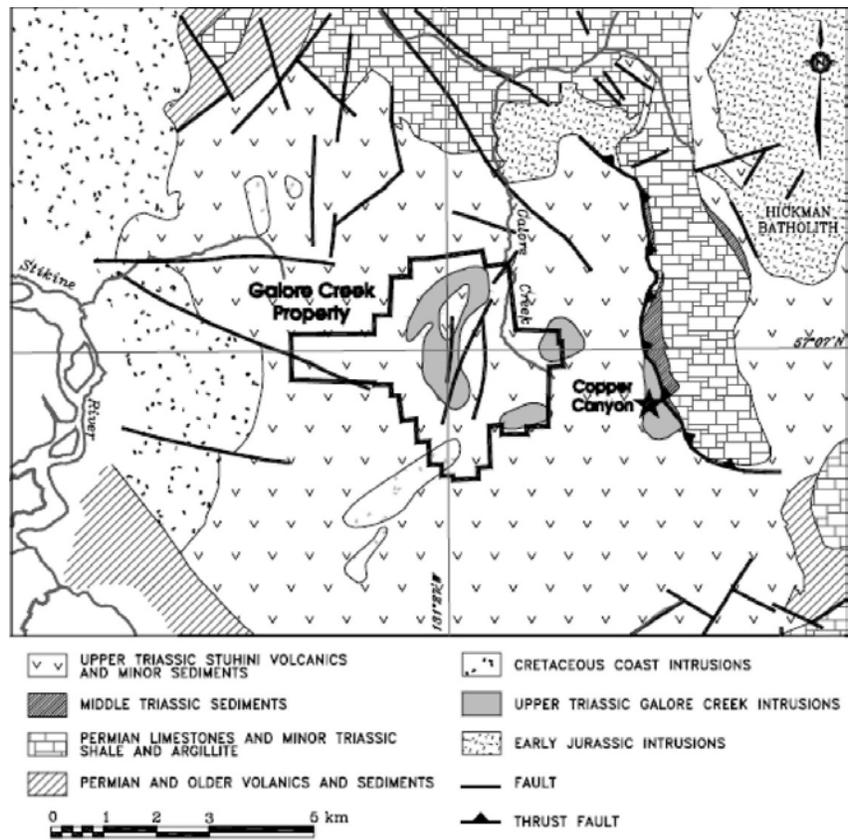
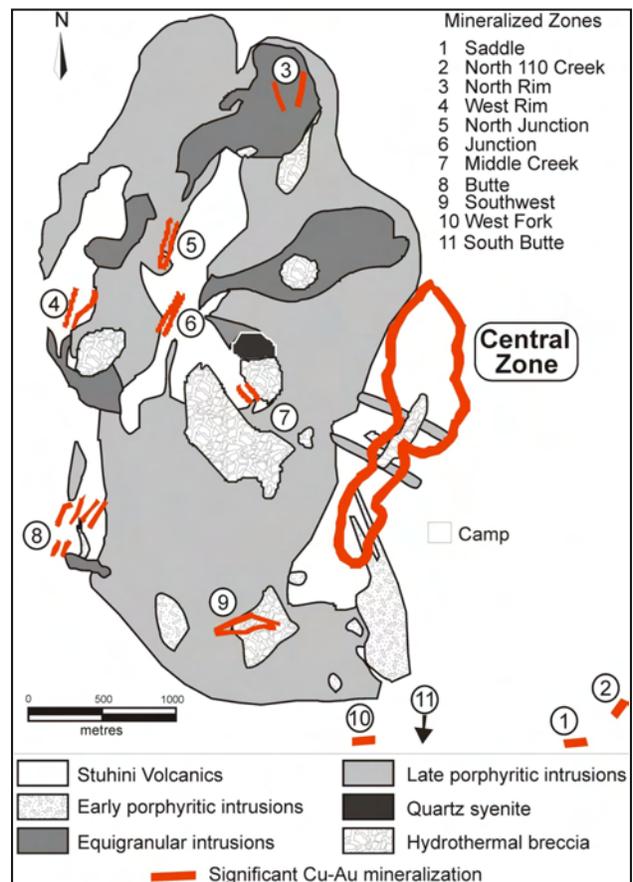


Figure 12. Summary map illustrating mapped geology of the Galore Creek deposits (after Enns et al., 1995).



Within the core of the Central zone, there occurs an associated 'Ca-K-silicate' assemblage, characterized by the addition of a dark brown garnet with locally occurring diopside, epidote and plagioclase. This assemblage appears to be localized where the high-temperature K-silicate altering fluids encountered calcic mafic rocks from which they derived Ca and precipitated garnet. Decreasing Ca in the alteration from the core region to the north and south of the Central zone is accompanied by generally increasing magnetite and early hematite.

Intermediate Argillic Alteration

Intermediate argillic alteration, composed of green sericite, carbonate and minor chlorite, appears most intense in the upper parts of the pre-mineral intrusion and usually overprints K-silicate alteration. Older magnetite is altered to hematite. Sericite affects all volcanic units as well as the pre-mineral and, to a lesser extent, post-mineral porphyry dikes. The paragenetic relationship of the alteration assemblages suggests that the intermediate argillic alteration was largely peripheral to the main centres of Cu and Au mineralization. Intermediate argillically altered rocks are intruded by post-mineral porphyry bodies.

Sericite-Anhydrite-Carbonate (SAC) Alteration

Sericite-anhydrite-carbonate alteration overprints early alteration phases and is locally extensive at the outer margins of the Central zone. In the southern part of the Central zone, it is accompanied by late hematite. In the northern part of the Central zone, it is marked by increasing pyrite±hematite and decreasing bornite-chalcopyrite, suggesting that Cu was remobilized during this alteration. In the core of the Central zone, sericite-anhydrite-carbonate alteration is poorly developed and patchy in occurrence.

Propylitic Alteration

An epidote-chlorite assemblage, locally accompanied by garnet, is present in post-mineral megacrystic porphyry bodies and penetrated for a few metres into their wallrocks.

MINERALIZATION

Sulphide minerals are closely associated with intense, pervasive K-silicate alteration as replacement, disseminated and fracture-controlled chalcopyrite with locally abundant bornite. Higher Au values are normally associated with bornite, which is better developed in the North and South gold lenses, relative to the Cu-enriched core of the Central zone. The Central zone is elongated in a north-northwesterly (015°) direction and dips steeply to the west. It is 1700 m in length and 200 to 500 m wide, and has been traced to a depth of 450 m through drilling, remaining open below that. In the west and south, mineralized rock is truncated by post-mineral megacrystic porphyry dikes.

Intense sericite-anhydrite-carbonate alteration has obliterated sulphide-mineralized rock in the northwestern part of the Central zone. In the north, mineralized volcanic

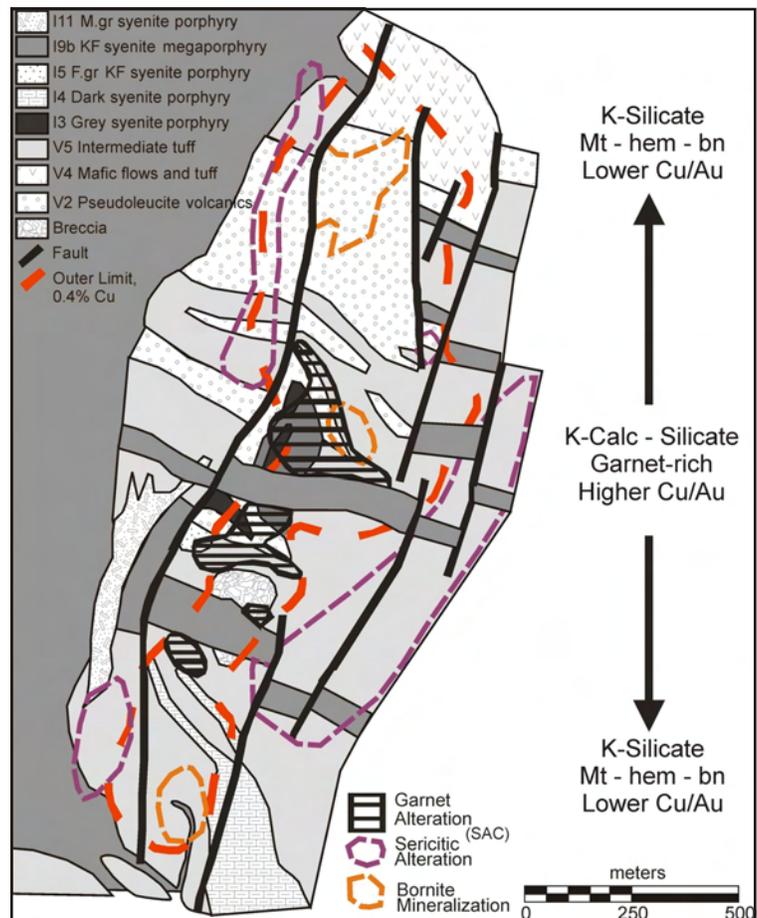


Figure 13. Distribution of the principal styles of alteration shown in relation to the Galore Creek geology, including gross metal ratios (after Enns et al., 1995).

rocks end abruptly against a thick sequence of barren epiclastic sedimentary and volcanic rocks. The Central zone has considerable internal variation in sulphide minerals and alteration mineral assemblages. Hydrothermal alteration assemblages change from Ca-K-silicate in the core to intense K-silicate assemblages toward the north and south parts of the zone. In terms of Au-Ag-Cu replacement, the most favourable volcanic rocks are pseudoleucite-bearing rocks in the north and crystal tuff in the south. Augite-bearing volcanic and volcanoclastic rocks in the north have low to moderate Cu grades. Gold values are highest in the northern and southern portions of the Central zone, where significant disseminated bornite, magnetite and hematite are present. Lower Au grades correlate with an intense Ca-K-silicate altered core. Chalcopyrite is the most important Cu mineral and occurs as replacements, disseminations and fracture fillings throughout the zone. Pyrite increases in abundance to the east of the Central zone, reaching concentrations of up to 5%. Minor supergene Cu is present, primarily as malachite, azurite and chrysocolla on fractures within 60 m of the surface.

GARNET PARAGENESIS AS A GUIDE TO THE EVOLUTION OF THE GALORE CREEK PORPHYRY DEPOSIT

Galore Creek is unique among the alkalic porphyry Cu-Au deposits in the abundance of garnet-rich alteration.

Garnet coexists with biotite, K-feldspar, anhydrite and apatite in the core of the Central zone, where it replaces early porphyry dikes and adjacent volcanic wallrocks. This alteration grades outwards into a conventional K-silicate assemblage of biotite, K-feldspar, magnetite and apatite. Garnet is characterized by growth zones marked by prominent colour variations, entrapment of primary fluid inclusions and episodic coprecipitation with, or replacement by, anhydrite. Fluid inclusion characteristics and chemical cycling are consistent with the formation of alteration and mineralization by release of magmatic fluids early in the igneous sequence at Galore Creek. Extended garnet growth at the high temperatures indicated by fluid inclusions suggests that the hostrocks sat and 'stewed' in a hydrothermal fluid-dominated system. The composition of the fluids, dominated by NaCl, KCl and CaCl₂, is consistent with the alteration assemblage K-feldspar, biotite, apatite, anhydrite, garnet and anhydrite. It also suggests that the alteration was occurring in a fluid-buffered system in which the hostrock composition had little control over the ultimate style or composition of alteration and possibly the ore assemblage.

FUTURE WORK

Ongoing integration of detailed structural, geochemical and geochronological information is essential to the development of an improved alkalic porphyry deposit model. While this work is in the initial stages, the overall goal of the project is to build a view of the structural and geological architecture, alteration zonation patterns and mineral chemistry at each of the study sites. Current studies will be augmented by a new study initiated at the Lorraine deposit. This latter deposit has perhaps some of the most abnormal characteristics of the alkalic porphyry systems, and suggests that sulphide mineral deposition bridged the transition from magmatic-segregation to magmatic-hydrothermal deposits. The Lorraine deposits also appear to represent the deepest possible level of formation in the alkalic porphyry environment. Defining the hydrothermal features of each deposit, combined with available data from deposits around the world, will thus provide the basis for establishing the characteristics of the intrusion-centred systems at a range of inferred deposit depths.

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