

Alkalic Cu-Au Deposits of British Columbia: Sulfur Isotope Zonation as a Guide to Mineral Exploration

By C.L. Deyell^{1,2} and R.M. Tosdal¹

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INTRODUCTION

Cu-Au porphyry deposits associated with alkalic igneous rocks are known in only a few mineral provinces worldwide and some of the best-known examples are from British Columbia (*e.g.*, Galore Creek, Mt Polley, Afton/Ajax, Copper Mountain). The Lachlan Fold Belt of New South Wales (Australia), the other major alkalic porphyry province (*e.g.*, Cadia, Goonumbla), and other isolated alkalic systems are known from the Philippines (Dinkidi), Greece (Skouries) and Colorado (Allard Stock).

Alkalic porphyry deposits are of economic significance and represent some of the world's highest grade porphyry gold resources (*e.g.*, Ridgeway: 53 Mt @ 2.5 g/t Au, 0.77% Cu or 4.26 Moz Au; Cadia Far East: 290 Mt @ 0.98 g/t Au, 0.36% Cu or 9.13 Moz Au). In British Columbia, the alkalic porphyry systems at Copper Mountain, Mount Milligan and Galore Creek have a combined resource of over 900 Mt (Lang *et al.*, 1995). New exploration at Afton, Galore Creek and Lorraine has added significant resources.

Alkalic porphyry deposits present difficult exploration targets for several reasons. The high-grade metal concentrations are typically associated with small volume pipe-like intrusions that may have areal extents of only a few hundred square metres (Wilson *et al.*, 2002). The alkalic systems also have no associated advanced argillic alteration assemblages, and phyllic alteration is late and typically restricted to fault zones. Supergene enrichment is poorly developed due to the low pyrite contents of the hypogene alteration assemblages (Cooke *et al.*, 2002). Furthermore, the lack of extensive peripheral hypogene alteration hinders identifying the focus for fluid flow more than several hundred metres away from the mineralized porphyry centre. Effective exploration therefore requires tools to

recognize subtle or cryptic alteration zones or geochemical dispersion halos that highlight proximity to a mineralized intrusive centre. The focus of this study is the application of sulfur isotope analyzes to alkalic Cu-Au systems in British Columbia to test whether this technique can aid in the exploration of porphyry-style mineralization in this region.

BACKGROUND

Initial research in alkalic porphyry deposits of Australia and the Philippines has suggested that systematic vertical and lateral sulfur isotopic zonation surrounds several mineralized porphyry complexes (*e.g.*, Goonumbla and Cada, NSW; Lickfold, 2001; Wilson, 2003; Didipio, Philippines; Wolfe, 2001). Data collected by the Centre for Ore Deposit Research (CODES) at the University of Tasmania indicates sulfide compositions in these systems range from -2 to -10‰. The most negative values typically occur towards the top of the mineralized monzonite pipes, with a return to near-zero values with distance upward and/or outwards from the pipe. Several enigmatic sulfide compositions between -16 and -19‰ have been detected in the core of the Goonumbla quartz monzonite porphyries at depths of 1 km below the surface (Lickfold, 2001). These low values cannot be explained by contamination by biogenic sulfur, as has been argued for the Galore Creek deposit, British Columbia (Shannon *et al.*, 1983), since the Goonumbla sulfides occur in the core of an intrusive complex hosted by a near-coeval volcanic sequence.

The initial studies described above led to the obvious question of whether sulfur isotopes can provide a "magic-bullet" for exploration and a means to vector toward sulfide when faced with chloritic and propylitically altered rocks that are distal to the ore. Despite the suggestive evidence, the temporal controls on the isotopic zonation have not been tested adequately in either the Australian examples or elsewhere in the world. The trend towards negative sulfur isotopic compositions of sulfide minerals upwards through the monzonite bodies is thought to relate at least in part to sulfide deposition from an oxidized (sulfate predominant) fluid. Whether this mechanism in

¹ CODES, University of Tasmania, Hobart, Tasmania, Australia

² MDRU, University of British Columbia, Vancouver, BC

conjunction with cooling can account for the isotope systematics of alkalic porphyry deposits remains to be tested. It is furthermore still unclear what causes the zonation. It is possible that mixing of two sulfur sources may have occurred, and/or that wall rock buffering of redox conditions may have been influential in controlling the observed sulfur isotope zonation (D. Cooke, pers comm, 2004). Regardless, the zonation has been shown to be a robust, predictable phenomenon, and at least one major exploration company has had success using sulfur isotopes as a vector to delineate new Cu-Au occurrences. However, before sulfur isotope mapping can be applied widely, it must be established whether the zonation is a phenomenon common, or not, to these deposits on a worldwide basis.

THIS STUDY

In contrast to the Australian and Philippine deposits, very little data is currently available regarding the sulfur isotope signature of alkalic systems in British Columbia. The goals of this study are therefore to determine whether systematic sulfur isotopic zonation of sulfide minerals might also characterize alkalic porphyry deposits in this region.

This study has been completed over a two-year period and has been funded through the Rocks to Riches program, managed by the British Columbia and Yukon Chamber of Mines (BCYCM). Preliminary research conducted in the 2003 field season consisted of investigations at several major deposits including Galore Creek, Afton, Red Chris, Mt Polley, and Lorraine (Fig. 1). Initial results uncovered some interesting trends (Deyell *et al.*, 2004). In particular, data for Mt Polley showed a trend of decreasing $\delta^{34}\text{S}_{\text{sulfide}}$ values with increasing Au grades, suggesting redox controls were significant for Au deposition. Similar trends were noted in the Bishop Zone at Lorraine, although samples from the Lower Main Zone in this same deposit appear to have an opposite trend with a positive correlation between Au grade and $\delta^{34}\text{S}_{\text{sulfide}}$ values. As a follow-up, research in the 2004 field season was focused only on the Lorraine and Mt Polley deposits. The aim was to fully test the origin and significance of the zonation and relation to Cu-Au mineralization at specific alkalic porphyry deposits.

In this paper, we report results from the 2003 and 2004 studies, which includes the combined research at Lorraine and Mt Polley as well as a summary of the preliminary investigations at the Red Chris, Galore Creek and Afton deposits. The sulfur isotopic data is only summarized in the chapter; the complete analytical data is available at <http://www.em.gov.bc.ca/Mining/Geosurv/Publications/catalog/catfldwk.htm> or at www.mdru.ubc.ca.



Figure 1. Location map showing the location of selected alkalic porphyry Cu-Au deposits in British Columbia.

METHODS

The 2004 study included ten days of fieldwork at Lorraine and Mt Polley during July and August. This work consisted primarily of core logging and sampling with specific focus on the distribution of sulfide species and sampling over a range of rock types, alteration assemblages, and metal grades. The sulfides were extracted manually using a hand-held drill (Dremel tool). Care was taken to ensure pure mineral separates although in the case of very fine-grained samples and intergrown sulfides, some contamination or mixed sulfide samples could not be avoided.

Sulfur isotopic analyses were completed at the United States Geological Survey (USGS) Isotope Laboratory in Denver (Colorado, USA) and the University of Tasmania Central Science Laboratory in Hobart (Australia). The USGS lab $\delta^{34}\text{S}$ analyses were completed using an on-line method with an elemental analyzer coupled to a Micromass Optima mass spectrometer following the method of Giesemann *et al.* (1994). The University of Tasmania lab uses conventional sulfur isotope techniques according to Robinson and Kusakabe (1975) and measurements are performed on a VG Sira Series II mass spectrometer. Analytical uncertainties for both techniques are estimated at ± 0.1 per mil (‰).

RESULTS

Lorraine

The Lorraine deposit is located in the northern Intermontane Belt approximately 280 km northwest of Prince George (Fig. 1). The bulk of the previously de-

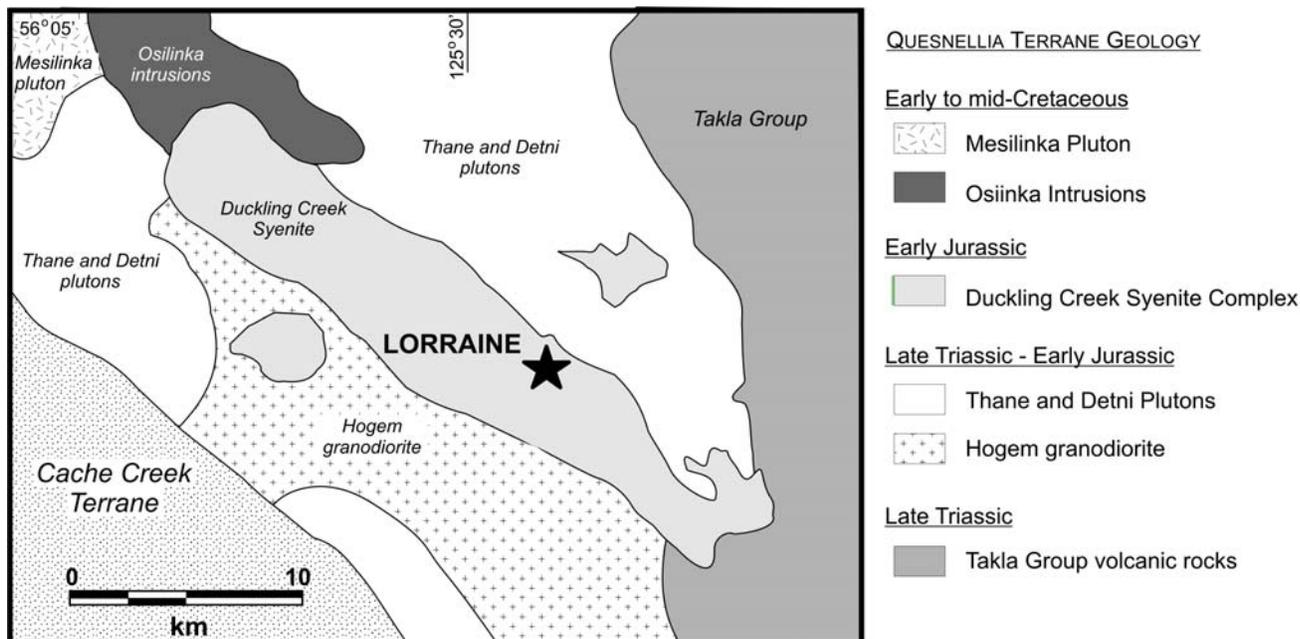


Figure 2. Location and regional geological setting of the Lorraine deposit. Modified from Nixon and Peatfield (2003).

fined resource (32 Mt at 0.66% Cu, 0.25 g/t Au; Morton, 2003) occurs within a roughly circular area comprising the Lower Main, Main and Bishop zones. Several other peripheral mineral occurrences have also been identified (e.g., Copper Peak, All Alone Dome). The property is hosted entirely by the Hogem Batholith, a late Triassic to Middle Jurassic intrusion of calc-alkalic to alkalic composition (Garnett, 1978). All known mineralization is associated with alkalic rocks of the Duckling Creek Syenite Complex (Fig. 2), which is a discrete unit within the composite (182 to 162 Ma) Hogem Batholith (Bishop *et al.*, 1994).

The Duckling Creek Suite forms a northwesterly trending, elongate unit approximately 35 km long and averaging 8 km wide (Morton, 2003). In the Lorraine area, the syenite complex was originally subdivided into a foliated syenite 'migmatite' that enveloped and partially intruded a suite of pyroxenites and monzonitic to dioritic rocks (Garnett, 1978). Younger crosscutting leucocratic syenite and potassium feldspar porphyry dikes and sills are common.

The geology of the Lorraine area was reviewed by Nixon and Peatfield (2003) who made several significant revisions. They subdivided the Duckling Creek Syenite Complex into two distinct intrusive phases (Fig. 3). Phase 1 is an early plutonic suite of feldspathic pyroxenite, mela-syenite and monzonite. Phase 2 is a younger suite of leuco-syenites and potassium feldspar megacrystic porphyries. The 'migmatite' described previously is thought to represent local zones of metasomatic compositional layering and veining in more extensive areas of minor intrusive

activity and potassic alteration (Nixon and Peatfield, 2003).

Alteration related to Cu-Au mineralization at Lorraine has been documented in several studies (Wilkinson *et al.*, 1976; Garnett, 1978; Bishop *et al.*, 1995; Nixon and Peatfield, 2003). This alteration is dominated by alkalic, particularly potassium, metasomatism consisting of an early stage of secondary biotite development and pervasive potassium feldspar deposition that affects all rock units. Local sodium metasomatism is a pervasive replacement of plagioclase by albite and conversion of augite pyroxene to aegirine pyroxene (Morton, 2003). Late-stage weak sericite and propylitic (chlorite-epidote-carbonate) alteration is also recognized (Bishop *et al.*, 1994). Late quartz veins occur locally. An unusual calc-silicate assemblage of diopsidic clinopyroxene, garnet, albite, epidote, biotite and apatite was also recognized in the BM area by Nixon and Peatfield (2003).

TABLE 1. METAL RATIOS* FOR MINERALIZED ZONES AT LORRAINE.

	Au/Cu	Ag/Cu	Ag/Au
Lower Main	28.6	15.1	18.9
Upper Main	0.8	11.4	37.7
Bishop	1.1	32.5	116.1

*based on mean assay results from Eastfield Resources drill programs from 1993 to 2002. Ratios are calculated on the basis of % Cu, g/t Au, g/t Ag. Data below detection assigned values of 50% of detection limit for the purposes of these calculations.

Sulfide minerals are chalcopyrite and bornite with secondary chalcocite, digenite and rare covellite. Pyrite is a minor constituent. The sulfides are fine- to medium-grained disseminations with lesser sulfide-bearing veinlets and fractures fillings (Bishop *et al.*, 1994). No systematic spatial zonation of sulfide mineralogy has been recognized. Average gold (grams per tonne) to copper (weight percent) ratios are much lower than those at other alkalic deposits (*e.g.*, Afton, Copper Mountain, Mt Polley: Stanley, 1993) with values of about 0.8 in the Lower Main zone and 1.1 in the Bishop zone (Table 1). It has been suggested that at least part of the mineralization is magmatic in origin, due to the occurrence of copper sulfides as blebs and “net-textured” semi-massive sulfide in pyroxenite (Bishop *et al.*, 1994; Morton, 2003).

SULFUR ISOTOPE STUDY

Prior to the study in 2003, no sulfur isotope data were available for the Lorraine property. Samples for the 2003 study were selected from skeleton core held by Eastfield Resources in Vancouver. These samples consisted mainly of material from the Lower Main and Bishop zones with a few additional samples from the Upper Main zone and peripheral mineral showings. Reported sulfur isotope data for sulfides ranged from -0.2 to -10.2‰, with average values of -4.1‰ in the Lower Main zone and -2.3‰ in the Bishop zone (Deyell *et al.*, 2004). These data could not be correlated reliably with different rock or alteration types, since only the skeleton core was available at that time. However, the

Phase 1 (pre-mineralization)

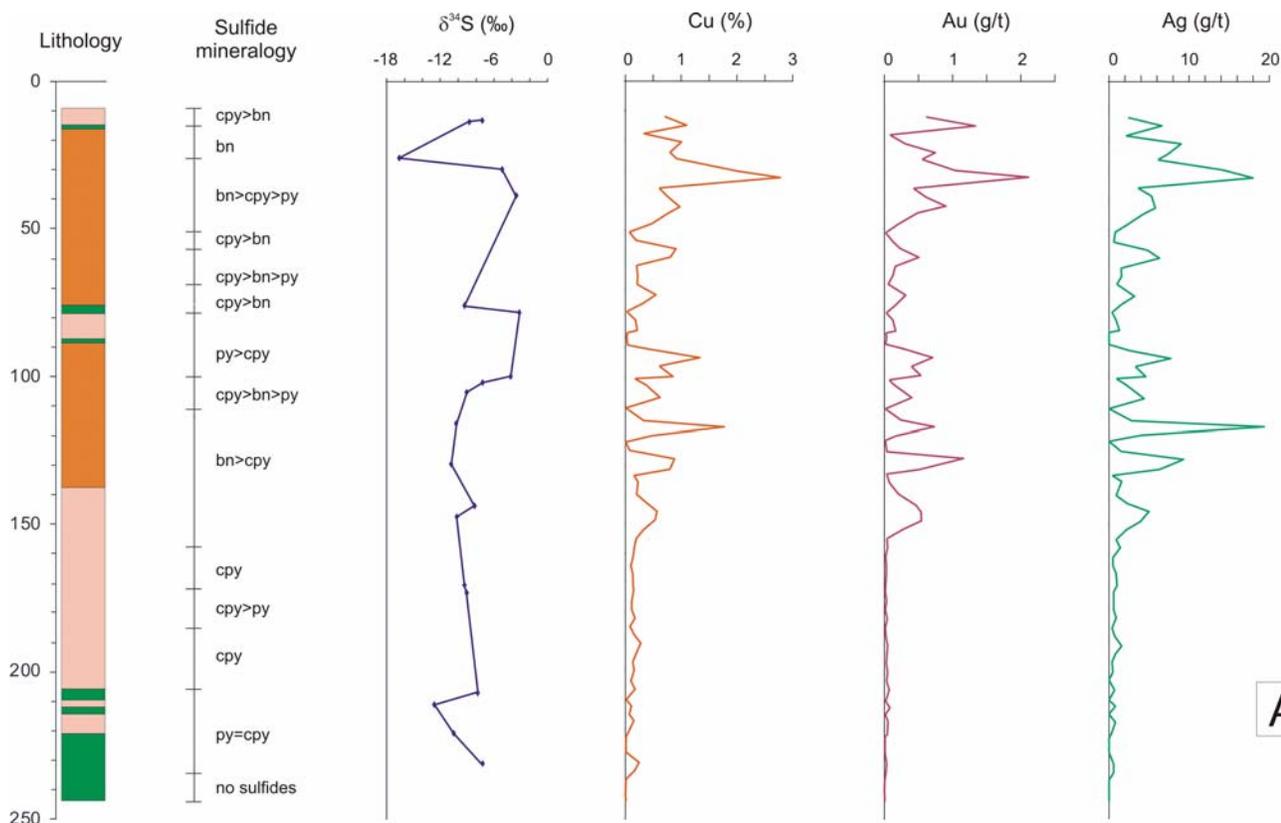
- **Mesocratic monzonite-syenite**
Pinkish grey, medium-grained, roughly equigranular plutonic rocks ranging from monzonitic to syenitic compositions. Distinguished from mela-syenites by lower abundance of mafics (typically 15-20%) consisting of pyroxene, biotite, +/- amphibole.
- **Mela-syenite**
Greenish-grey, medium to coarse-grained, biotite-clinopyroxene Kspar syenite with 25-40% mafics.
- **Feldspathic pyroxenite**
Dark greenish black, medium to coarse-grained biotite clinopyroxene to melanocratic syenodiorite (with variable feldspar component). This unit includes the three varieties described by Nixon and Peatfield (2003); clinopyroxene with interstitial feldspar, oikocrystic pyroxenite, and pyroxenite with large, roughly tabular, Kspar crystals.

Phase 2 (pre- to syn- mineralization)

- **Kspar megacrystic porphyry dykes**
Coarse-grained, grey to white (rarely pale pink) tabular to blocky Kspar crystals with local accessory clinopyroxene and/or magnetite.
- **Quartz vein**
Coarse white quartz vein with chalcopyrite-bornite.
(Not a significant lithological unit, but does occur as a mapable zone in DDH L95-13; Fig. 4).

Figure 3. Summary of major geological units at Lorraine (and legend for lithological drill logs shown in Figure 4). Geological information is summarized from Nixon and Peatfield (2003) with additional observations from this study.

correlation of $\delta^{34}\text{S}_{\text{sulfide}}$ data to metal grades was significantly different for samples from the Lower Main and Bishop zones. The Bishop zone samples have a strong correlation between decreasing $\delta^{34}\text{S}$ values and Au grade, but nearly an opposite, although less well defined, trend was suggested for samples from the Lower Main zone.



A

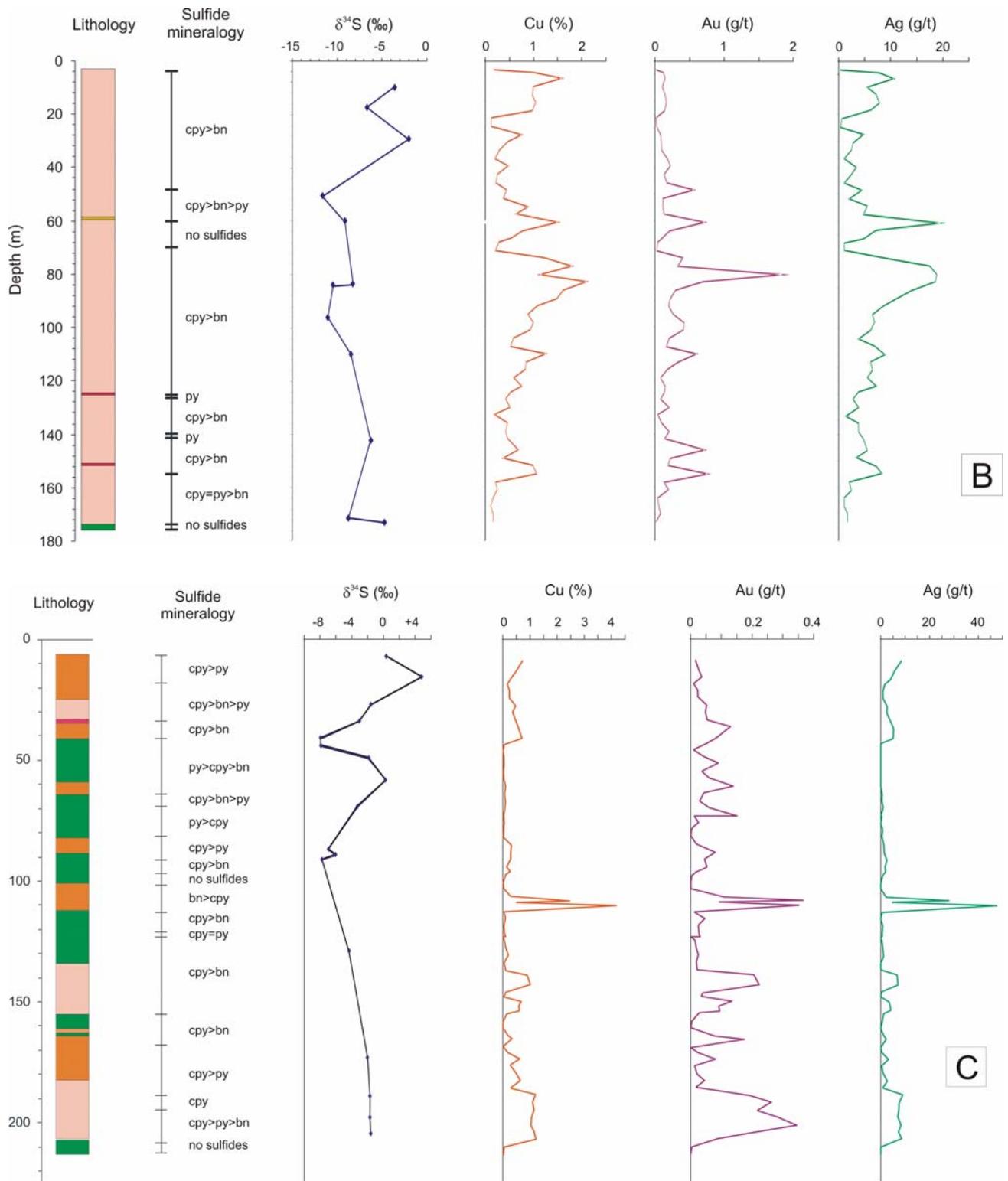


Figure 4. Schematic logs for selected drillholes through each of the major mineralized zones at Lorraine. A: Lower Main, DDH 2002-62; B: Upper Main, DDH L-95-13; C: Bishop, DDH 2001-58. See Figure 3 for geological legend. Assay values summarized from Eastfield Resources data.

Schematic drillhole logs were constructed for one hole in each of the Lower Main, Upper Main, and Bishop zones (Fig. 4). These logs illustrate the relationship between rock type, dominant sulfide

mineral species, $\delta^{34}\text{S}_{\text{sulfide}}$ values, and metal grades, although locally intense but extremely variable potassic alteration proximal to mineralized zones commonly made it difficult to identify primary rock types. The re-

relationship between $\delta^{34}\text{S}_{\text{sulfide}}$ data and Au grades as well as Cu-Au metal ratios is shown in Figure 5. There is some indication of increasing $\delta^{34}\text{S}$ values with Cu-Au

ratios at both the Upper Main and Bishop zones, but there is also significant scatter in the data.

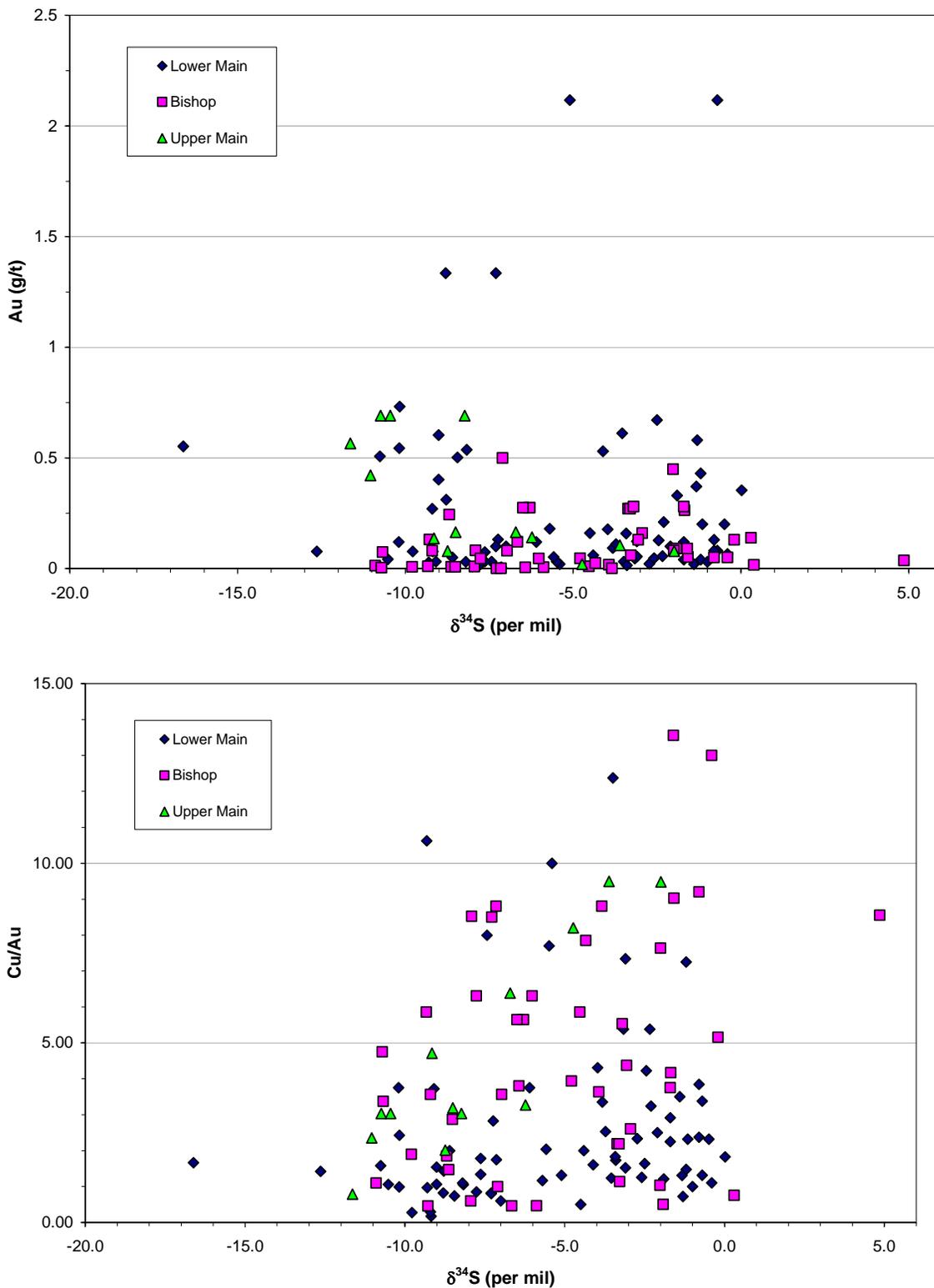


Figure 5. A (top): Lorraine $\delta^{34}\text{S}$ data plotted against Au (g/t) values. B (bottom): Lorraine $\delta^{34}\text{S}$ data plotted against Cu/Au values (Cu as %, Au as g/t). All metal values taken from assay intervals provided by Eastfield Resources.

TABLE 2. SUMMARY OF $\delta^{34}\text{S}$ DATA (AS PER MIL) FOR LORRAINE.

Area	Range $\delta^{34}\text{S}$	Average $\delta^{34}\text{S}$
Lower Main	0 to -16.6	-5.3
Bishop	+4.9 to -10.9	-5.0
Upper Main	-2.0 to -11.6	-7.8

Overall, the sulfur isotope data indicate that most of the analyzed material from Lorraine is not primary magmatic sulfides, as originally proposed by Bishop *et al.* (1994), since the data vary over a range of nearly 20%. Furthermore, magmatic values are generally assumed to be consistently near zero, which is not the case here. The available data are consistent, however, with a hydrothermal origin and are comparable to magmatic-hydrothermal sulfide compositions from porphyry Cu-Au systems. More detailed analysis of the dataset will be required to understand the relationship between sulfur isotope values and mineralization, alteration types, and/or igneous units.

Mt Polley

The Mt Polley deposit is located in the Quesnel terrane (Fig. 1) near Likely, British Columbia. The deposit was mined between 1997 and 2001 and produced 27.7 Mt of ore from the Cariboo and Bell pits (Fig. 6). The property has been inactive since 2001 but still contains an estimated 31.9 Mt of ore in the Bell and unexploited Springer deposits (Imperial Metals, pers comm, 2004). In August 2003, the discovery of a previously unknown, high-grade copper-gold zone, the NE zone, located approximately 1.5 km to the northeast of the Bell pit, initiated a major exploration and drilling program which led to the identification of several mineralized zones (Fig. 6). On-going exploration continues to intersect significant Cu and Au grades (*see* Imperial Metals for details).

The Mt Polley area is underlain by Jurassic and Triassic intrusive rocks of the Mt Polley intrusive complex. This complex consists of multiple intrusions of diorite to plagioclase porphyry to monzonite compositions that intruded sedimentary and volcanic rocks of the Nicola Group (Fraser *et al.*, 1995). The intrusions are associated with several intrusion breccias, which is a breccia with igneous matrix. The igneous breccias and numerous hydrothermal breccias form the main host for Cu-Au mineralization. In the Bell, Cariboo and Springer zones, the hydrothermal breccias are dominated by either actinolite, biotite, magnetite or albite, although the relationships between the different phases are unclear (Fraser *et al.*, 1995). Alteration consists of a core zone, coincident with the hydrothermal and intrusion breccias (Fig. 7), that is characterized by pervasive potassic alteration surround-

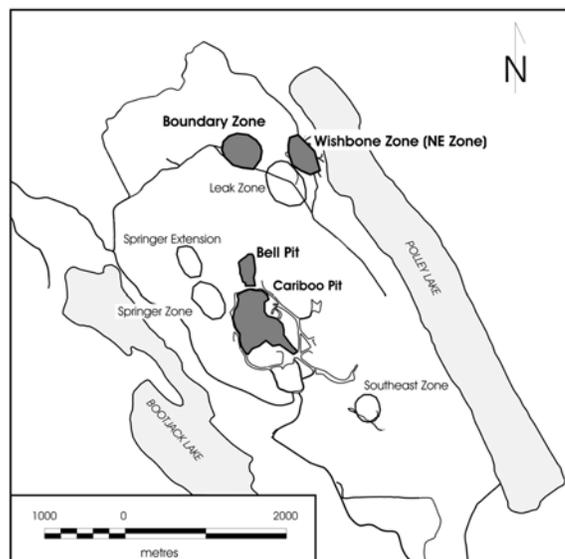


Figure 6. The Mt Polley deposit showing locations of major mineralized zones.

ed by a garnet-epidote zone, and rimmed by propylitic (epidote-pyrite-calcite) assemblages (Hodgson *et al.*, 1976). Mineralization occurs primarily as disseminations of chalcopyrite-magnetite-bornite, with increasing pyrite and diminishing bornite outwards from the core of the deposit. Sulfides also occur as blebs in the matrix of the hydrothermal breccias and abundant veins. Copper and gold values are closely correlated, and generally correspond to high magnetite concentration (Fraser *et al.*, 1995).

The recently discovered NE zone has several significant differences to the Bell and Cariboo areas. The geology of this region is dominated by plagioclase and potassium feldspar-pyritic intrusions that are locally megacrystic. In addition, there are lesser monzonite with late augite porphyry and mafic dykes. Mineralization is spatially associated with intrusion breccias (Fig. 8a) that are heterolithic, matrix- to clast-supported, with a fine- to medium-grained, equigranular monzonite matrix. Sulfide minerals are dominated by bornite, chalcopyrite and lesser pyrite. The sulfides are coarse-grained clots, irregular veins, or fine disseminations overprinting the matrix of the intrusion breccias and locally the breccia clasts as well. Sulfide minerals are also in veins and as disseminations in coherent intrusive phases. A sulfide zonation was recognized in cross-section with a core of bornite±chalcopyrite, rimmed by chalcopyrite-dominant sulfide assemblages, with pyrite ± chalcopyrite at the margins (*see* Fig. 10c).

Alteration in the NE zone (K. Ross, pers comm, 2004) consists of an early, pervasive, potassium metasomatism associated with little to no biotite. A distinct magnetite-garnet-apatite assemblage is pre- to

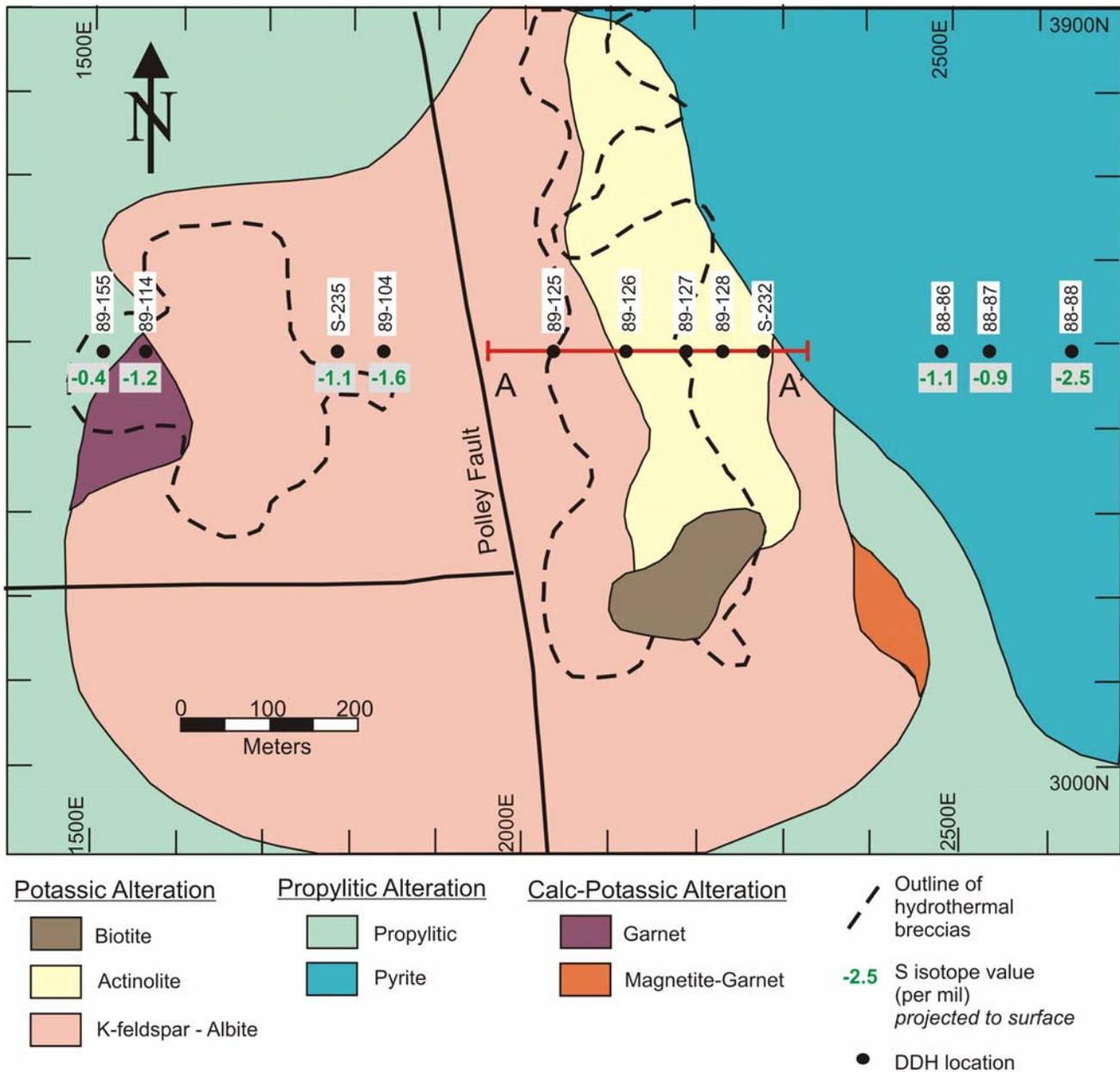


Figure 7. Alteration map of 'central zone', Mt Polley (slightly modified from Fraser *et al.*, 1995) showing line of section 3460N that was selected for detailed $\delta^{34}\text{S}$ sampling (see Fig. 9). Also shown are locations of DDH that were sampled in 2003 for preliminary sulfur isotope investigations and $\delta^{34}\text{S}$ results as per mil values (see Supplemental data for sample depths).

syn-mineral. This assemblage may overlap with a slightly later syn- to post-mineral assemblage dominated by a Ca-Al silicate (clinozoisite or prehnite?) and is associated with albite-calcite, lesser garnet, and minor diopside. Late alteration consisting of calcite-sericite-albite-chlorite is widespread. Chlorite-carbonate-pyrite alteration is rare but occurs locally peripheral to the brecciated zones and within the country rocks to the east of the main mineralized centre.

The Nordic zone, which is part of the Boundary Zone (Fig. 6), was examined briefly. Samples of one

drillhole (ND-04-01) have some similarities to the NE zone, although several significant differences were noted. In particular, sulfide minerals are primarily associated with a magnetite±garnet, clinozoisite or prehnite(?) +calcite breccia matrix (Fig. 8b). It is unclear whether this assemblage overprints an original intrusive matrix. Pyrite in association with chalcopyrite is more abundant in the core of the mineralized zone than in the NE zone. Bornite was not observed. In general, the Nordic zone is significantly more gold- and silver-rich than the NE zone (Imperial Metals, pers comm, 2004).

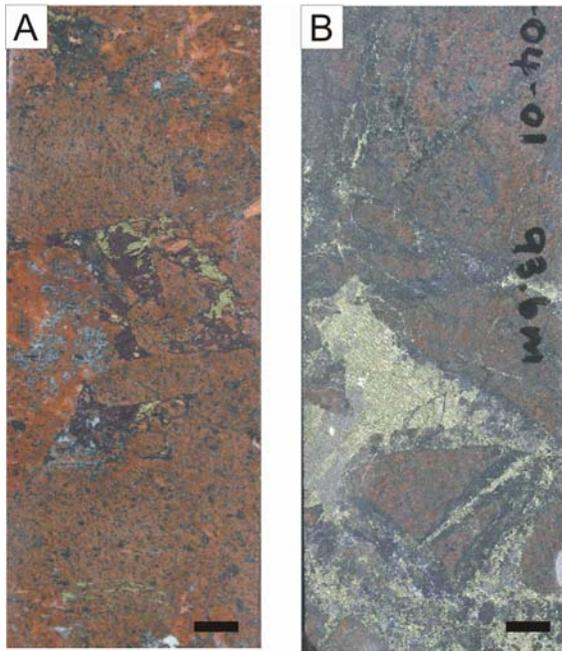


Figure 8. Photos of Mt Polley drillcore. A. NE Zone, bornite-chalcopyrite mineralization in matrix of intrusion breccia (DDH 04-29, 100.5m). B. Nordic Zone, chalcopyrite-pyrite-magnetite \pm garnet breccia cement (ND-04-01, 93.6m). Scale bars = 1 cm.

SULFUR ISOTOPE STUDY

Prior to the initiation of this study, no sulfur isotope data were available for the Mt Polley deposit. Samples for the preliminary 2003 study were obtained from a collection archived at MDRU from the study of Fraser *et al.* (1995) and from a short field visit in October 2003 by S. Ebert. The majority of the 2003 samples were selected from the Cariboo and Bell deposits (along section 3460N; Fig. 7). At that time, only three samples were taken from the NE zone.

The $\delta^{34}\text{S}_{\text{sulfide}}$ results ranged between +1.5 and -3.4‰, and $\delta^{34}\text{S}$ data for the Cariboo and Bell deposits were generally higher than those for samples from the NE zone (with average values of -0.4 and -3.2‰, respectively). In the Cariboo deposit, the highest $\delta^{34}\text{S}_{\text{sulfide}}$ data appeared to be spatially associated with a small body of plagioclase porphyry and intrusion breccia that forms the core of this zone. However outside of this area, the sulfur isotope data was limited and further work was required to define the details of any zonation trends present in the dataset. Further work was also necessary to determine the nature and source of $\delta^{34}\text{S}_{\text{sulfide}}$ variation throughout the Mt Polley region.

Samples from 2004 were focused on section 3460N in the Cariboo zone (in five selected drillholes; Fig. 9). Detailed sampling was also completed along one cross-section (section 18) through the core of the NE zone (Fig. 10). Only one drillhole (ND-04-01) was sampled in the Nordic zone.

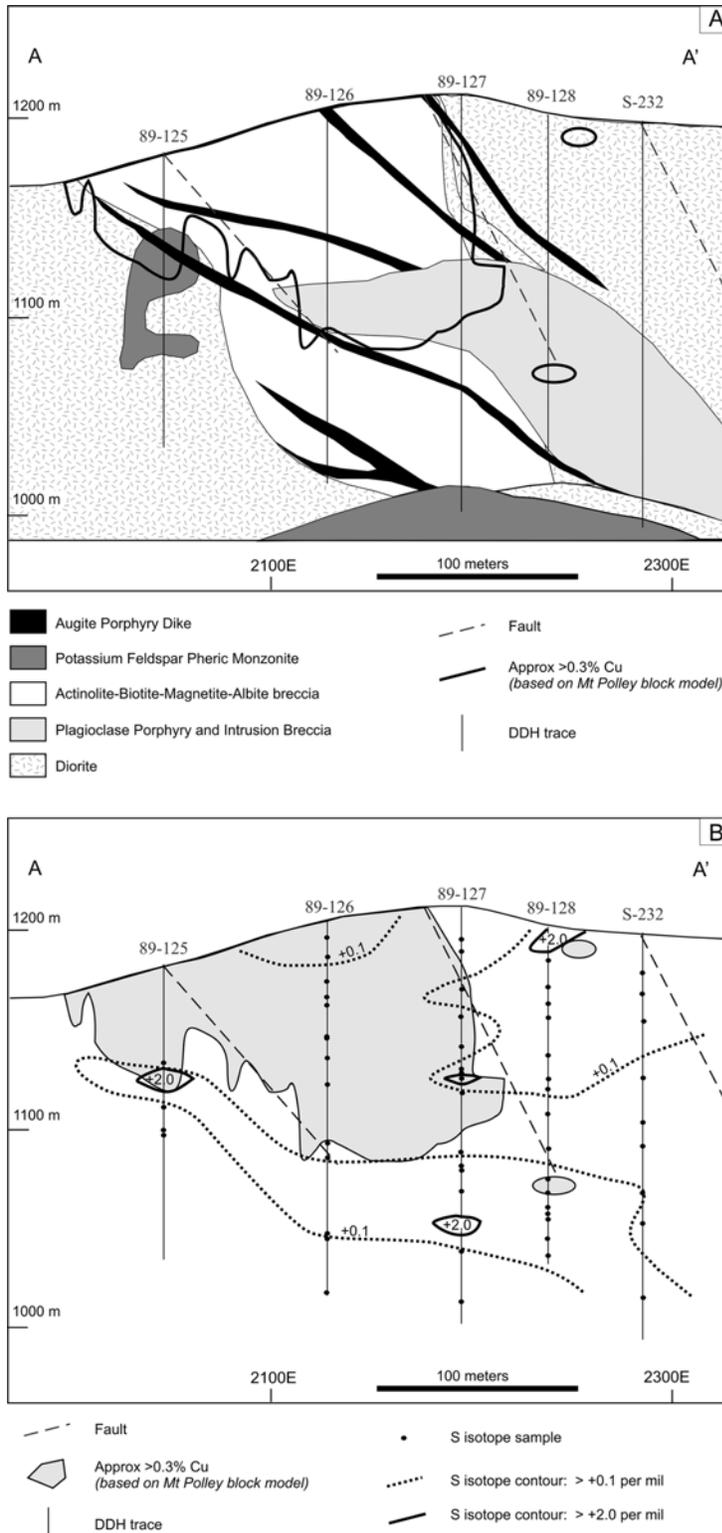
Sulfur isotope results from Cariboo zone (Fig. 9) range from -2.3 to +2.4‰. An average $\delta^{34}\text{S}_{\text{sulfide}}$ value of +0.2‰ for the Cariboo samples is significantly higher than that for samples in the NE zone (*see* Fig. 10). A distinct sulfur isotope zonation is apparent in cross-section (Fig. 9B), with the Cu ore zone surrounded by high $\delta^{34}\text{S}_{\text{sulfide}}$ values. Negative $\delta^{34}\text{S}$ values are spatially associated with the top and middle of the plagioclase porphyry and intrusion breccia as mapped by Fraser *et al.* (1995). These results agree with the conclusions of Fraser *et al.* (1995) who suggested that the porphyry and associated breccia are the source of fluids responsible for mineralization in the Cariboo zone.

In contrast to the Cariboo deposit, chalcopyrite with lesser pyrite and bornite from the NE zone have significantly lower $\delta^{34}\text{S}_{\text{sulfide}}$ values, which range from -1.1 to -7.0‰. In cross-section (Fig. 10b), $\delta^{34}\text{S}_{\text{cpy}}$ values appear to be zoned with minimum values concentrated at depth to the east-northeast, slightly offset from the core of bornite mineralization. The more negative $\delta^{34}\text{S}$ values are coincident with intrusion and hydrothermal brecciation, although a range of values is recognized through these rock types. It is possible that the data reflect the path of oxidized, mineralizing fluids from depth although further investigations should identify any structural controls and/or alteration zonation associated with this area.

Red Chris

The Red Chris Cu-Au deposit is located in the Stikine Terrane of northwestern British Columbia (Fig. 1), in the Totogga Lake area approximately 80 km south of Dease Lake. Exploration for Cu-Au in this area is recorded as early as 1956 (Baker *et al.*, 1997), although it has never been mined. The property was acquired by bcMetals Corporation in 2003, who have since defined an inferred resource of 28.2 Mt at 0.62% Cu and 0.5 g/t Au (data from bcMetals website, Nov. 2003).

The geology and nature of Cu-Au mineralization of the Red Chris area is summarized from Baker *et al.* (1997). The geology of the region is dominated by Mesozoic volcanic rocks that include the Middle to Upper Triassic Stuhini Group and the overlying Lower Jurassic Hazelton Group. Cu-Au mineralization is associated with the Red Stock, which is an elongate, Early Jurassic subvolcanic intrusion that cuts the volcano-sedimentary suite of the Stuhini Group. The Red Stock is a multi-phase porphyritic to equigranular, hornblende quartz monzodiorite to monzonite. Alteration is characterized by abundant early potassic assemblages overprinted by later sericitic and argillic alteration. Sulfide minerals are dominantly vein-hosted chalcopyrite, lesser bornite, and negligible pyrite. Bornite becomes more abundant than chalcopyrite with increasing depth. Minor galena and sphalerite are late phases (Baker *et al.*, 1997). Unusual features of the de-



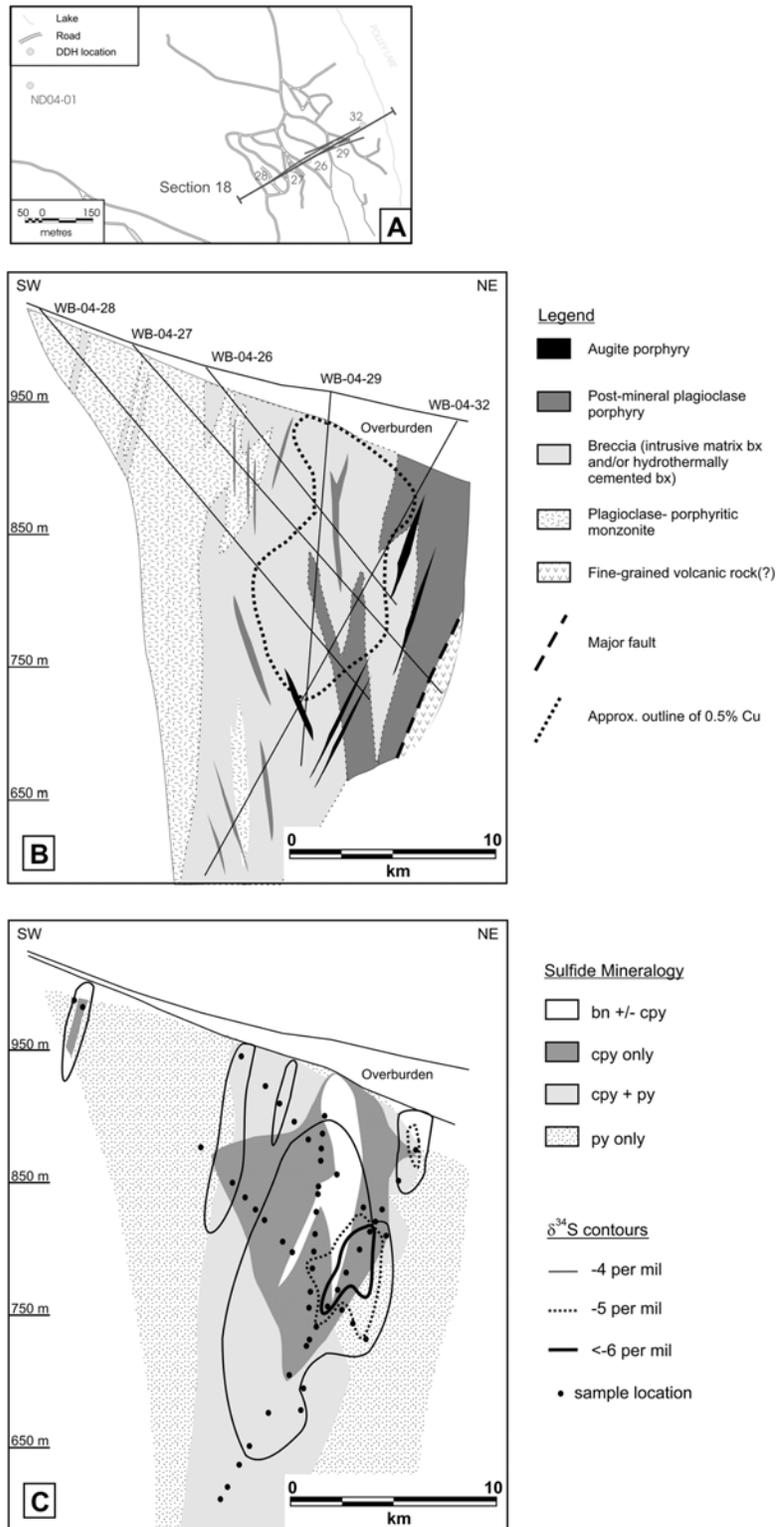


Figure 10. Schematic cross-section through the NE zone, Mt Polley. A. General location of Section 18 (mine grid) across the NE zone that was sampled for this study. General geology (modified from K. Ross, pers comm, 2004) and outline of Cu mineralization. C. Sulfide mineral zonation and contours of $\delta^{34}\text{S}_{\text{cpy}}$ data from this study.

posit include the abundance of carbonate alteration and veins, and the occurrence of mineralized quartz vein stockwork in the Main Phase of the Red Stock. Red

Chris also lacks Na- and Ca-bearing silicate alteration assemblages. Both features are more typical of calc-alkalic porphyry deposits than other alkalic deposits of

British Columbia (Baker *et al.*, 1997). Despite those differences, Red Chris is more similar in many ways to the alkalic porphyry deposits of New South Wales in Australia (*e.g.*, Goonumbla, Lickfold *et al.*, 2003; Cadia, Wilson *et al.*, 2003), which also contain well-mineralized quartz vein stockwork.

SULFUR ISOTOPE STUDY

Only limited sulfur isotope data for sulfides and sulfates from the Red Chris property were available prior to this study (T. Baker and J. Thompson, pers comm, 1997). This data indicated that the sulfide $\delta^{34}\text{S}$ values range from -3.6 to $+0.6\text{‰}$ with sulfate $\delta^{34}\text{S}$ values ranging from $+12.5$ to $+16.0\text{‰}$. This current study sought to test the variability in sulfur isotope compositions with different alteration styles and with Cu/Au ratios. Unfortunately, only a small number of samples were available for this work and were gathered from a collection held by T. Baker (James Cook University, Australia) and MDRU.

The $\delta^{34}\text{S}_{\text{sulfide}}$ determined during this study are similar to the initial results (T. Baker and J. Thompson, pers comm, 1997) with values ranging from $+0.9$ to -5.0‰ . Most samples are from the Main Zone and the results are shown in cross-section in Figure 11 (section 50000E). The data is relatively sparse, although in general, positive $\delta^{34}\text{S}_{\text{sulfide}}$ values form the core of the strong quartz-sulfide stockwork zones and at depth. There is significant variability at the margins and tops

of the intense stockwork zones, although $\delta^{34}\text{S}_{\text{sulfide}}$ data are generally negative.

Results from this study are consistent with decreasing temperature outwards from the core of the mineralized zones and/or with decreasing depth. Preliminary fluid inclusion data from T. Baker and J. Thompson (pers comm, 1997) suggest a temperature range from over 500° to 300°C , or over at least 200°C during the potassic and quartz-sericite-carbonate vein and associated sulfide events. At these temperatures (from 500° to 300°C), calculated $\Delta^{34}\text{S}_{\text{sulfate-pyrite}}$ values based on fractionation equations in Ohmoto and Rye (1979) would decrease by approximately 7‰ under equilibrium conditions. Although no $\delta^{34}\text{S}_{\text{sulfate}}$ data are available for anhydrite associated with the mineralizing event, a 7‰ $\Delta^{34}\text{S}_{\text{sulfate-pyrite}}$ difference could reasonably account for the 4 to 5‰ range in $\delta^{34}\text{S}_{\text{sulfide}}$ data indicated in Figure 11. A more comprehensive study would be required to confirm the role of cooling as the source of $\delta^{34}\text{S}_{\text{sulfide}}$ variation, and determine the extent of the $\delta^{34}\text{S}$ zonation in the adjacent unmineralized wall rocks.

Galore Creek

The Galore Creek porphyry system is located in the Stikine terrane of northwestern British Columbia at the western margin of the Intermontane Belt (Fig. 1). The region contains Cu-Au mineralization in several discrete zones. The largest zones, the Central, Southwest and

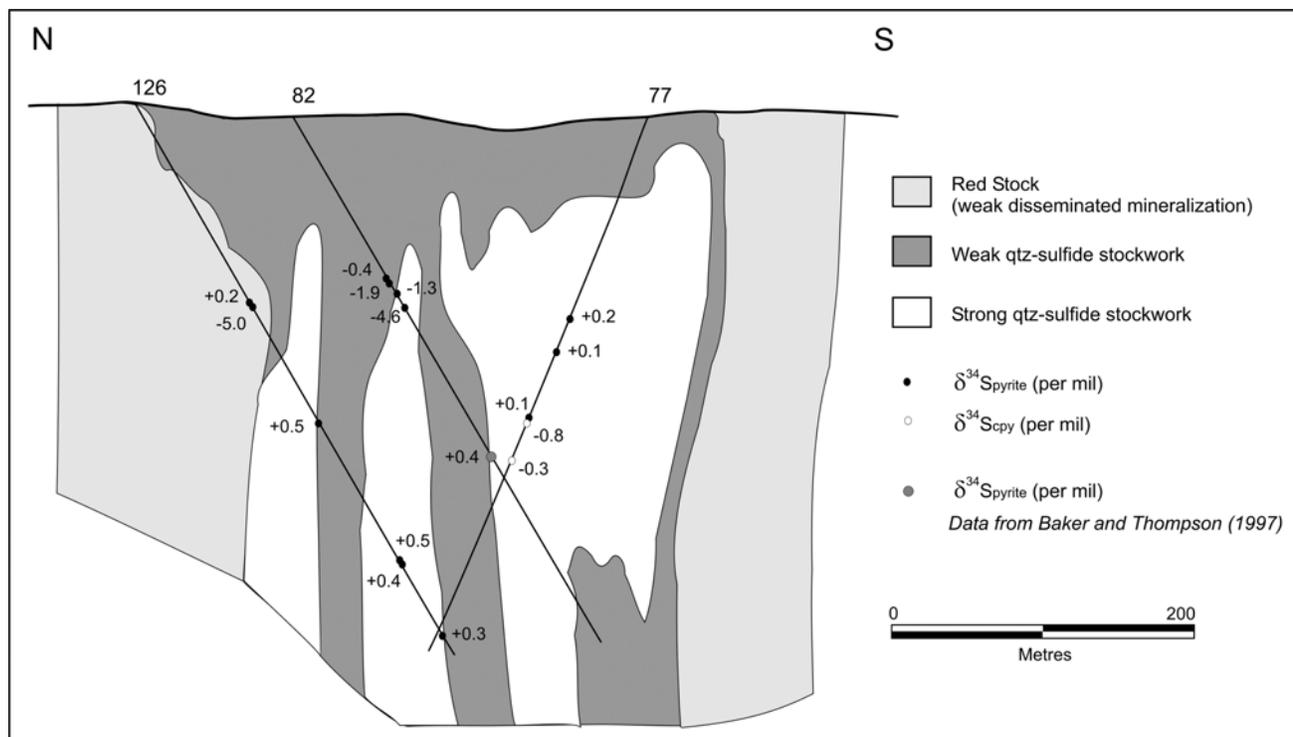


Figure 11. Schematic cross-section (Section 50000E; looking east) through the Main Zone of the Red Chris deposit (modified from Blanchflower, 1995). $\delta^{34}\text{S}_{\text{sulfide}}$ data from this study (with approximate sample locations) are shown, as well as one data point located on this sections from Baker and Thompson (pers comm, 1997). See Baker *et al.* (1997) for section location and local geology.

Junction zones (Fig. 12), contain an identified resource of 284 Mt at 0.67% Cu (Enns *et al.*, 1995). The Galore Creek area is dominated by Upper Triassic to Lower Jurassic alkalic volcanic rocks and syenite intrusions (Enns *et al.*, 1995). Multiple intrusive phases are recognized, and include pre-, inter-, late- and post-mineral phases (Enns *et al.*, 1995; Simpson, 2003). The intrusions are dominantly silica-undersaturated, alkalic and metaluminous, although the youngest intrusive phase is weakly silica-saturated. Numerous breccias are also present and locally host significant sulfide mineral concentrations, particularly in the Southwest Zone (Enns *et al.*, 1995). In general, Cu and Au are associated most closely with pervasive K-silicate and lesser Ca-K silicate alteration as replacement, disseminated and

fracture-controlled chalcopyrite with locally abundant bornite. Higher Au values are normally associated with bornite (Simpson, 2003).

Copper to gold ratios are variable throughout the Galore Creek deposit. In the Central Zone, copper concentrations are fairly consistent although gold concentrations are variable and are closely associated with abundant bornite, magnetite and hematite in the northern and southern portions of this zone (Enns *et al.*, 1995). As a result, Cu/Au ratios are variable and are lowest to the north and south of the Central Zone core (Fig. 12). In the Southwest Zone, Cu/Au are variable and higher Au concentrations locally correspond to an increase in pyrite content (Enns *et al.*, 1995).

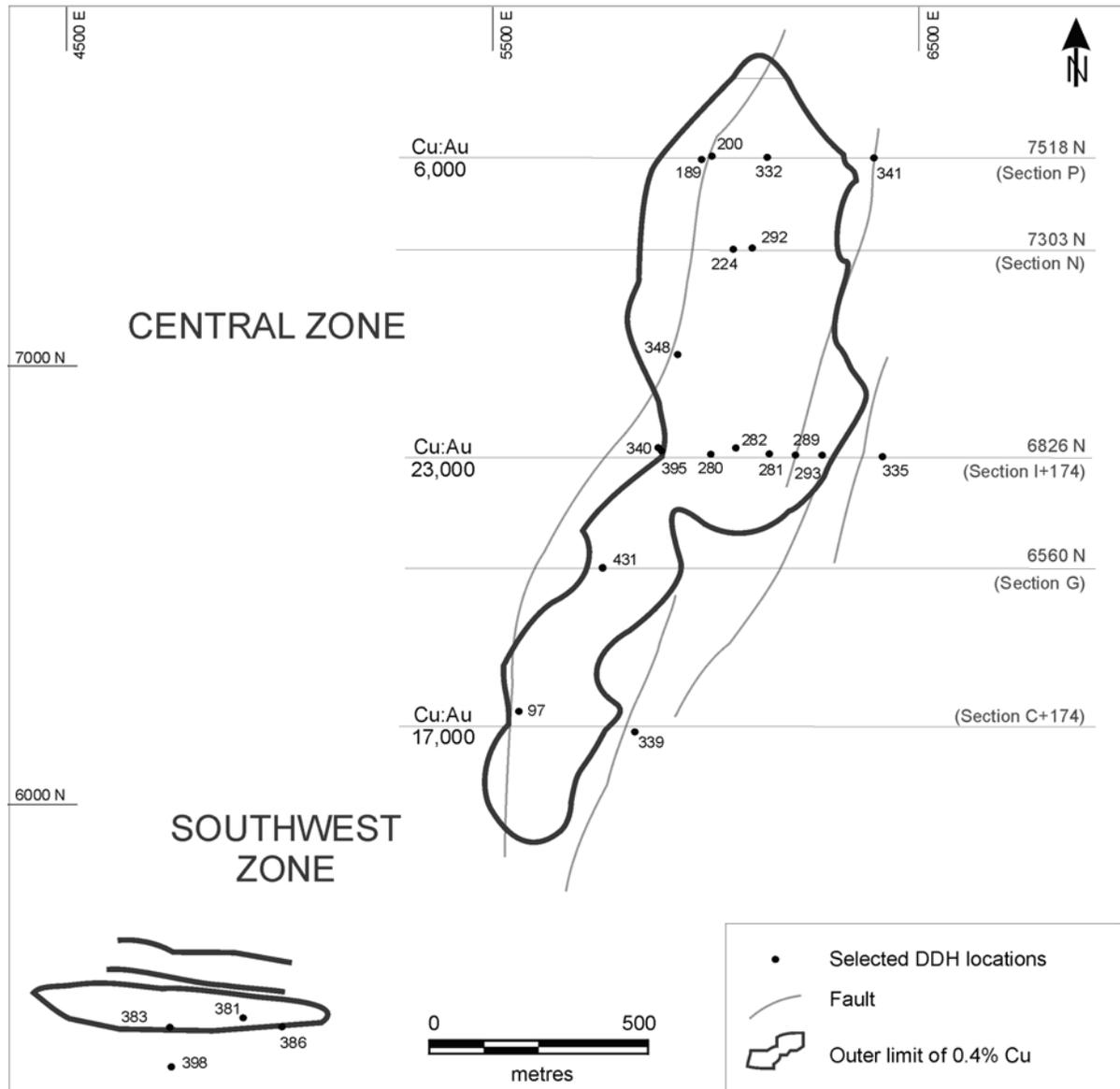


Figure 12. Map of the Galore Creek area showing location of the major mineralized areas (Central and Southwest Zones), diamond-drill hole locations from which the isotope samples were collected, and lines of section (adapted from Enns *et al.*, 1995).

SULFUR ISOTOPE STUDY

Prior to this study, limited sulfur isotope data for sulfides and sulfates at Galore Creek were acquired by J. Thompson and C. Stanley (MDRU). Their data suggest a range of $\delta^{34}\text{S}$ values from -9.9 to -6.4% for sulfides and $+5.0$ to $+7.4\%$ for sulfates (J. Thompson, pers comm, 2003) but sampling was restricted to the Central Zone.

In the current project, sulfide samples were obtained from a suite archived at MDRU. Twenty-nine samples of drillcore were selected along five cross-sections through the Central Zone, with an additional seven samples from the Southwest zone (Fig. 12). Sulfide $\delta^{34}\text{S}$ data range from -3.5 to -11.3% . Data for sulfides in the Central and Southwest zones are similar. Average $\delta^{34}\text{S}$ values are -7.3% and -6.5% , respectively. Copper and gold grades are not available for individual samples from these deposits, thus we are unable to comment on the correlation of isotope values with grade. However, the spatial distribution of isotope results (Fig. 13) does illustrate relatively higher average $\delta^{34}\text{S}$ values for sulfides at the northern and southern parts of the Central Zone, compared to the core of this zone. This core area contains on average lower Au grades in association with intense Ca-K silicate alteration (Enns *et al.*, 1995). In general, the sulfur

isotope zoning in the Galore Creek deposit is weak and is probably related to, or complicated by, the multi-phase intrusive-hydrothermal history in this district (Enns *et al.*, 1995). At this stage, not enough is known regarding the timing and relationship of the multiple intrusive-hydrothermal phases to constrain the origin or significance of the sulfur isotope results. A systematic paragenetic study of the magmatic and hydrothermal history would be required to fully understand the implications of the data.

Afton

The Afton property, located near Kamloops, British Columbia (Fig. 1), is the largest Cu-Au deposit in the Iron Mask Batholith district. The Afton mine produced 22.1 Mt of ore at 0.91% Cu and 0.67 g/t Au (Ross *et al.*, 1995) while in operation from 1977 to 1987. The property is currently owned by DRC Resources who have delineated an additional resource of over 51 Mt Cu (measured and indicated; DRC Resources, pers comm, 2004). The bulk of this resource is contained within a southwest trending lens that is roughly 200 to 250 m in thickness. The sulfide resource extends below and to the southwest of the current Afton pit (Fig. 14). Other nearby deposits include Ajax, Pothook and Crescent.

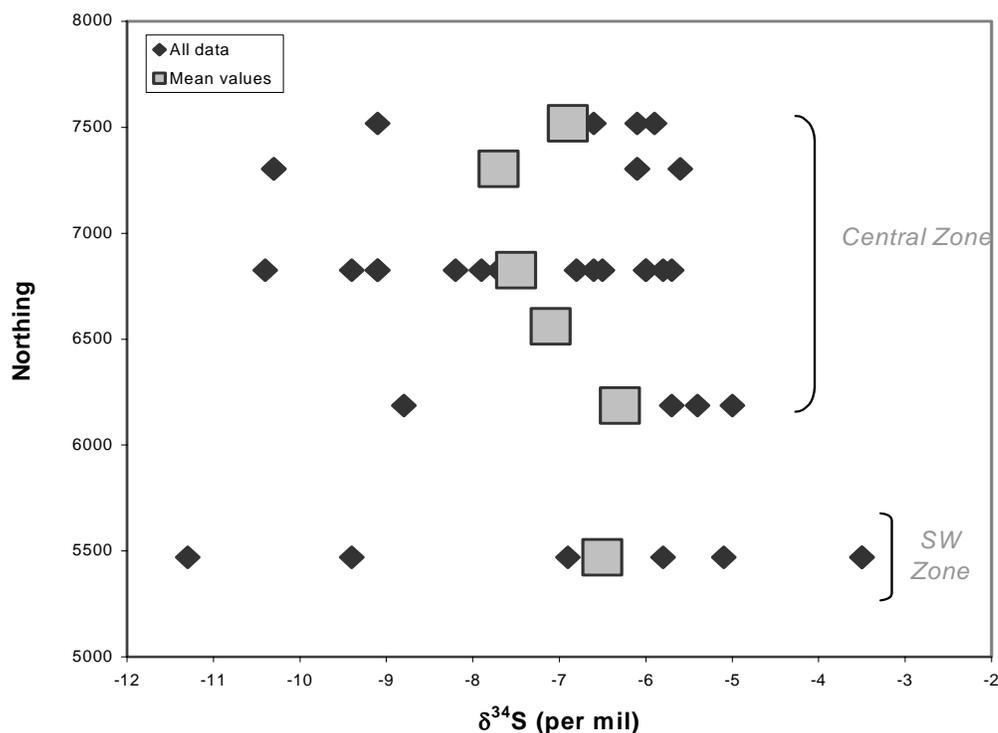


Figure 13. Distribution of Galore Creek $\delta^{34}\text{S}$ results from the 2003 study. Data are plotted according to their northing location. Individual data points are shown, as well as mean $\delta^{34}\text{S}$ values for each line of section.

All porphyry systems are hosted by the Iron Mask Batholith, an Early Jurassic composite alkalic intrusion that was emplaced into the Late Triassic Nicola Group composed of volcanic, volcanoclastic and minor sedimentary rocks. The batholith consists of two major plutons, the Cherry Creek pluton and the Iron Mask pluton; the latter is dominant around the Afton mine. The Iron Mask pluton includes four major intrusive phases; the Pothook diorite, Hybrid unit, Cherry Creek diorite-monzonite-syenite and the Sugarloaf diorite (after Ross *et al.*, 1995; Snyder and Russell, 1995). Minor picrite also occurs in several deposits in the Iron Mask Batholith, including Afton (Ross *et al.*, 1995). Volcanic and sedimentary rocks of the Tertiary Kamloops Group (Ewing, 1981) unconformably overlie the batholith.

The bulk of ore originally mined from the Afton pit was from a thick supergene zone that extended to depths of about 400 to 500 m (Kwong, 1987). This ore consisted primarily of native copper and chalcocite with minor cuprite, malachite and azurite. Hypogene ore consists of bornite and chalcopyrite with lesser chalcocite and covellite. Sulfides occur as disseminations and veinlets, with variable K-feldspar, albite, epidote, hematite, magnetite and carbonate (Kwong, 1987).

SULFUR ISOTOPE STUDY

Prior to this study, no $\delta^{34}\text{S}$ data were available for the Afton deposit. Sampling was completed on-site in July 2003, and no additional work was carried out in the 2004 study. The initial sulfur isotope sampling was focused along one long section, oriented roughly southwest along the length of known mineralization (Fig 15), including the Southwest zone (*see* Fig. 14). Several samples were also taken from smaller occurrences peripheral to the Afton pit to test the regional sulfur isotope signature.

The $\delta^{34}\text{S}$ data for the main mineralized area and the Southwest zone range from +3.6 to -8.0‰. Samples peripheral to the Afton pit, taken from Ajax, Big Onion and the Magnetite showings, also occur within this range. There are no obvious correlations of $\delta^{34}\text{S}_{\text{sulfide}}$ values to either Cu and Au grade, although less than half of the samples analyzed have associated assay data. Figure 15 shows the distribution of $\delta^{34}\text{S}$ data in cross-section and relative to the estimated position of the ore zone (0.5% Cu cut-off: DRC Resources, pers comm, 2003). There is considerable variability in the data although a zone of strongly depleted or negative $\delta^{34}\text{S}_{\text{sulfide}}$ values is apparent in the core of the known

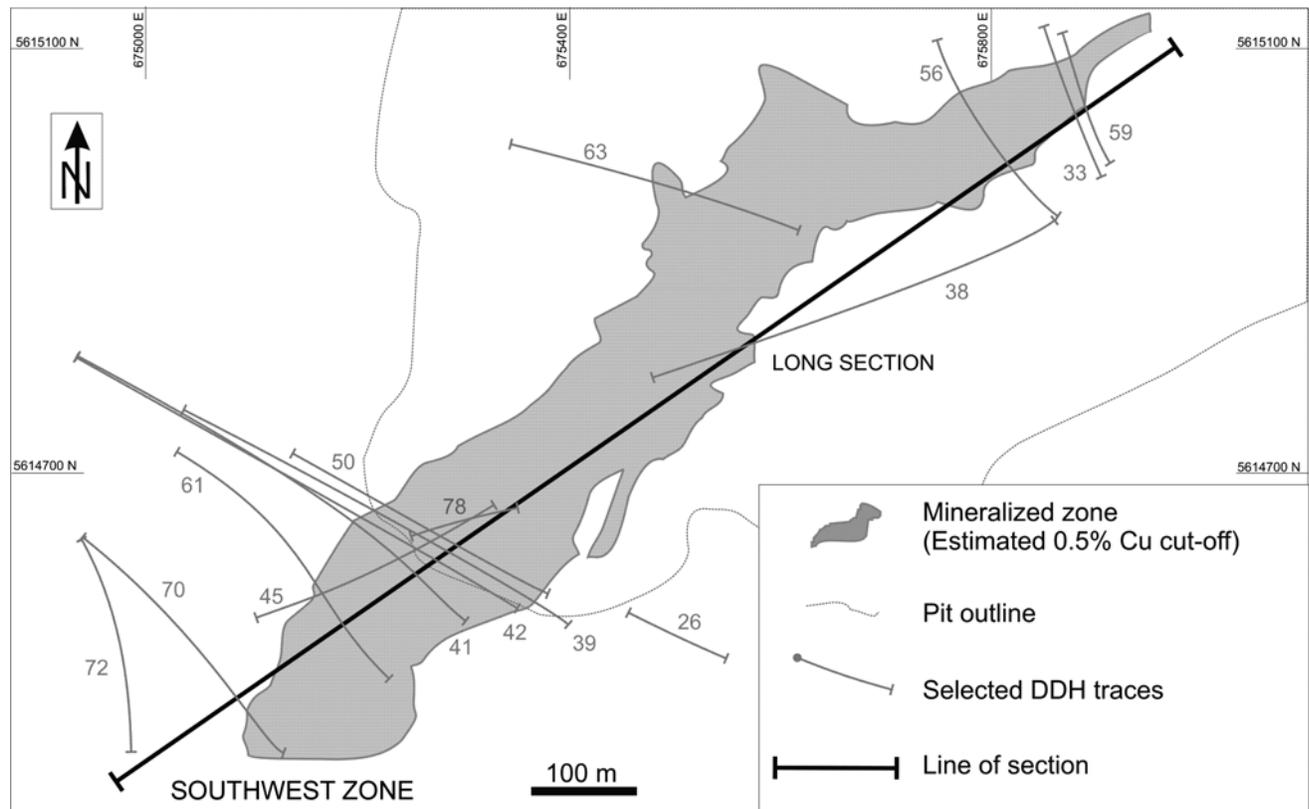


Figure 14. Plan view of the Afton area showing location of the hypogene mineralized zone delineated by DRC Resources. Also shown is the location of the cross-section detailed in Figure 15.

mineralized zone. This anomalous zone extends further to the southwest in DDH-70 (-7.1‰), although this drillhole has not been tested by assays. Negative $\delta^{34}\text{S}_{\text{sulfide}}$ values are also concentrated at the eastern margin of the mineralized zone, where they extend to surface. Only one anomalously positive $\delta^{34}\text{S}_{\text{sulfide}}$ value of +3.2‰ is recorded in the longitudinal section. It occurs at depth, at the margin of what has been modeled as a thin wedge of ore grade material (DRC Resources, pers comm, 2003) that likely lies along a fault or fracture zone.

Overall, the sulfur isotope zonation at Afton is well defined through the core of the main mineralized body. Discrete zones of anomalously high and low $\delta^{34}\text{S}_{\text{sulfide}}$ values may indicate domains of reduced and oxidized fluids, respectively, suggesting that fluid mixing along structural intersections may have contributed to ore deposition. A more thorough investigation into the nature of the ore and alteration assemblages, and the geometry of associated structures, would be required to fully understand the origin and significance of the sulfur isotope zonation.

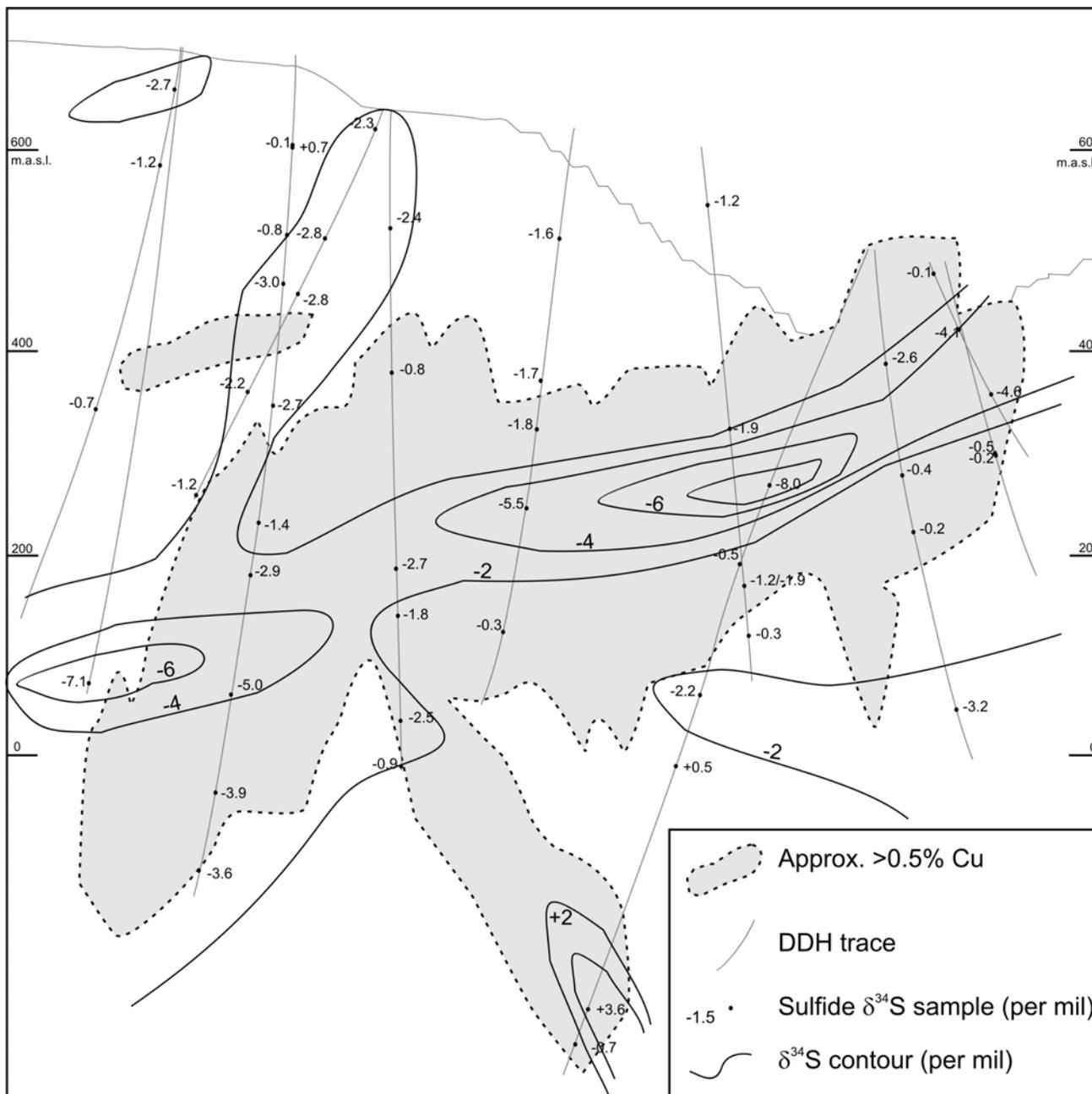


Figure 15. Afton long section showing $\delta^{34}\text{S}$ results and approximate position of ore zone outlined by 0.5% Cu cut-off (from DRC Resources, pers comm, 2003). Contours of $\delta^{34}\text{S}$ data at 2 per mil intervals are shown.

SUMMARY

This report summarizes data from a two-year study of sulfur isotope zonation in selected alkalic porphyry deposits in British Columbia. Preliminary data were collected for the Lorraine, Mt Polley, Red Chris, Afton and Galore Creek deposits in this first year of this study (2003). Initial results for Lorraine and Mt Polley in particular were of sufficient interest to warrant further work, and detailed sampling was completed on-site at these two deposits in July-August of 2004. Major findings are summarized as follows:

- Data from the Lorraine deposit are consistent with a magmatic-hydrothermal origin for mineralization, and not a strictly primary magmatic sulfide source. There is some indication of increasing $\delta^{34}\text{S}$ values with Cu-Au ratios in a few mineralized zones, but the relationship of $\delta^{34}\text{S}$ data with lithology, sulfide mineralogy, and metal grades needs to be tested further.
- At Mt Polley, detailed sulfur isotope analyses from the Cariboo zone suggests that the Cu ore zone is surrounded by high $\delta^{34}\text{S}_{\text{sulfide}}$ values. Negative $\delta^{34}\text{S}_{\text{sulfide}}$ values are spatially associated with plagioclase porphyry and related intrusion breccia. Similarly, the spatial distribution of $\delta^{34}\text{S}$ data at the NE zone suggests a strong relationship to intrusion and/or hydrothermal brecciation, and anomalous or negative values are slightly offset relative to a core of bornite \pm chalcopyrite deposition. In general, results indicate a consistent sulfur isotope zonation in both mineralized areas and suggest that the path of oxidized, and potentially metal-bearing fluid, can be traced from their source.
- At Red Chris, the data collected was limited to an existing sample suite from T. Baker and sample coverage is limited. In general, results are consistent with decreasing depositional temperature outwards from the core of the mineralized zones and/or with decreasing depth. Further work would be required to determine the extent of the $\delta^{34}\text{S}$ zonation into relatively unaltered and unmineralized wall rocks.
- Sulfur isotope data from the Galore Creek deposit do not exhibit any obvious spatial zonation, although there is some indication of more negative $\delta^{34}\text{S}$ values associated with lower Au grades in the core of the Central Zone. Further work would be required to understand the multi-phase intrusive-hydrothermal history of this district and their relation to sulfide deposition.
- Results from the Afton deposit indicate a distinct sulfur isotope zonation occurs within the deposit. There is a core of anomalous and strongly negative values in the centre of the main hypogene

mineralized zone. Local positive $\delta^{34}\text{S}$ values at depth may indicate the introduction of a different, more reduced, fluid source along structural features.

In summary, systematic sulfur isotopic zonation has been recognized within several alkalic Cu-Au deposits in British Columbia. While this technique may not be universally applicable, it may still prove to be a valuable exploration tool in those deposits where a predictable zonation pattern can be identified.

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