Sediment-Hosted Stratabound Copper-Silver-Cobalt Potential of the Creston Formation, Purcell Supergroup, Southeastern British Columbia (Parts of NTS 082G/03, /04, /05, /06, /12)

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Introduction

Siliciclastic sedimentary rocks contain significant Cu (Hitzman, 2000), so large cratonic basins are good source regions for this important resource. Sediment-hosted stratabound Cu deposits are the second most important global source of Cu, after porphyry Cu deposits, in terms of total resource (Singer, 1995). Major stratabound Cu deposits lie within the Kupferschiefer belt of Europe and the Zambian Copperbelt of Africa (Cailteux et al., 2005). The Paleoproterozoic Belt-Purcell Basin has a sediment thickness of at least 19 km within the central part of the basin in British Columbia (Cook and van der Velden, 1995) and up to 18 km in the United States (Winston and Link, 1993). This large thickness of sediment was deposited in a relatively short period of time (Evans et al., 2000), leading to the formation of numerous sediment-hosted stratabound Cu-Ag occurrences in the quartzite-dominated Revett Formation (Hayes and Einaudi, 1986; Boleneus et al., 2005). These deposits, including the Troy, Rock Creek and Montanore, are all located in western Montana (Figure 1).

In Canada, the Mesoproterozoic Purcell Basin hosts the Sullivan mine, one of the world's top SEDEX past-producers of Zn and Pb (Goodfellow and Lydon, 2007). This deposit is hosted in the Aldridge Formation of the lower Purcell Supergroup and, consequently, these strata have seen extensive base metal exploration. Rocks above the Aldridge Formation (middle and upper Purcell Supergroup) have received much less attention in BC, even though they host polymetallic veins (e.g., Paiement et al., 2007) and sediment-hosted Cu (±Ag±Co) occurrences.

A two-year research project was launched in 2007 to examine the stratabound Cu potential of the Purcell Supergroup. Field studies by the first author were conducted primarily in areas south and east of Cranbrook (NTS 082G/03, /04, /05, /06, /12), an area that was previously mapped by Höy and Carter (1988). Approximately 10 weeks of geological mapping, including a focused examination of the Creston Formation around Yahk Mountain in the McGillivray Range, were conducted in 2007 and 2008. Data and samples were collected for magnetic susceptibility measurements, lithogeochemical studies and a pilot biogeochemical survey. The Troy and Montanore stratabound Cu-Ag deposits of Montana were visited in order to better identify exploration strategies for this class of mineral deposit.

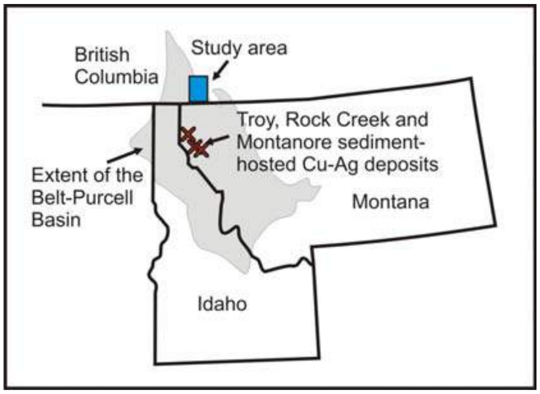

Figure 1. Approximate extent of the exposed Belt-Purcell Basin in British Columbia, Montana, Idaho and Washington (known as the 'Purcell Basin' in Canada and the 'Belt Basin' in the United States). The location of the study area (shown by the rectangle) and known sediment-hosted Cu deposits are also shown.

Initial results of a regional examination of known sediment-hosted Cu occurrences from the Purcell Supergroup were published by Hartlaub and Paradis (2008). The present paper moves to an examination of the potential for 'Revett style' (Cox et al., 2007) deposits in the Belt-Purcell Basin in Canada.

Geological Setting and Regional Stratigraphy of the Belt-Purcell Basin

The Mesoproterozoic Belt-Purcell Basin is an intracontinental rift system filled by marine and fluviatile

Keywords: *Purcell Supergroup, sediment-hosted Cu, red bed, Creston Formation, Revett Formation, stratabound, quartzite*

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sediments that extends from southeastern BC into Idaho, western Montana and eastern Washington (Höy, 1993; Elston et al., 2002; Lydon, 2007). It is known as the 'Belt Basin' (containing the Belt Supergroup strata) in the United States and the 'Purcell Basin' (Purcell Supergroup) in Canada. The basin developed as a branching system of sub-basins along basement structures and was later shortened and folded during several periods of deformation (Höy et al., 2000; Price and Sears, 2000). In southeastern BC, the oldest rocks of the Purcell Supergroup are exposed along the core and western margin of a large-scale anticlinorium (Purcell anticlinorium).

Mesoproterozoic rocks of the Purcell Basin in Canada have been stratigraphically subdivided in different ways by different authors working in different locations. A complete discussion of stratigraphic nomenclature and changes within the basin is available in Höy (1993), Winston and Link (1993) and Gardner and Johnston (2007). The lower 12 km of the basin are 'rift-fill' turbidite rocks, the Aldridge Formation in Canada, which are intruded by the mafic Moyie sills, dated at 1468 ±2 Ma (Anderson and Davis, 1995). The Creston, Kitchener and Van Creek formations overlie the Aldridge Formation, and constitute the middle succession of the Purcell Supergroup (Figures 2, 3). They represent the beginning of the 'rift-cover' sequence (Lydon, 2007) but predate the eruption of a thick package of flood basalts (the Purcell lavas or the Nicol Creek Formation). A porphyritic rhyolite in the Purcell lavas in Montana yielded an age of 1443 ±7 Ma (Evans et al., 2000). Directly overlying the flood basalts of the Nicol Creek Formation are coarse clastic and stromatolitic carbonate rocks of the Sheppard Formation. The shallow-water, fine-grained clastic rocks of the upper Purcell Supergroup include the Gateway, Phillips and Roosville formations (Höy, 1993).

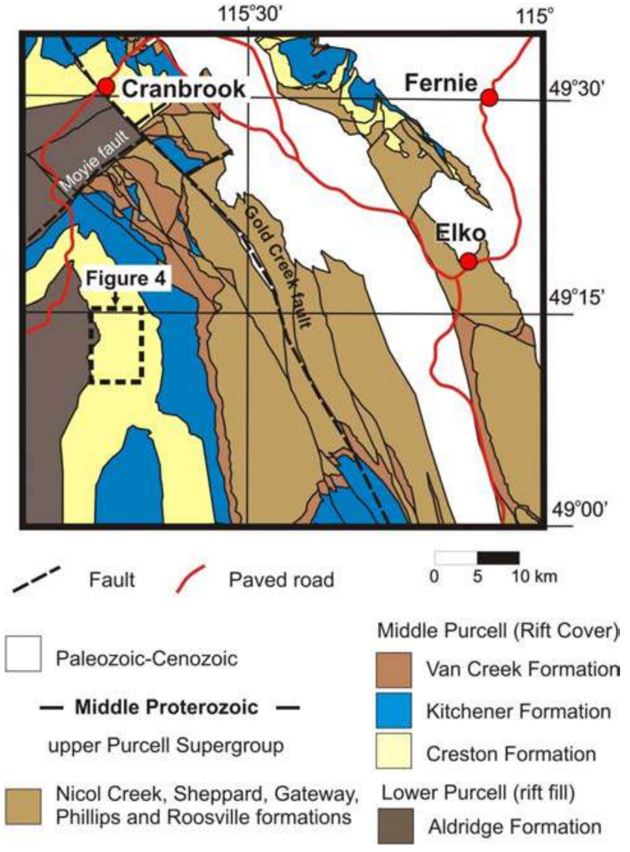

Figure 2. Simplified geology of the Purcell Supergroup (*modified from* Höy et al., 1995), showing the location of the study area (Figure 4).

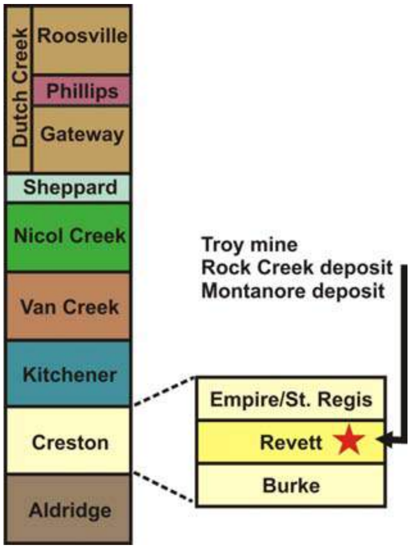

Figure 3. Simplified stratigraphic column for the Purcell Supergroup in the study area (*modified from* Höy, 1993).

In southeastern BC, the Purcell Basin has been folded along a north-northwest-trending axis and has been transported eastwards during regional compression associated with the late Cretaceous Rocky Mountain orogeny (Chandler, 2000; Höy et al., 2000; Price and Sears, 2000). A sub-greenschist grade of metamorphism exists throughout much of the Purcell Supergroup; however, the metamorphic grade is locally higher.

A glacial overburden blanket of variable thickness covers much of the Purcell Mountains south of Cranbrook. This overburden places a severe limitation on mapping and prospecting activities in the region. Outcrops are limited to steep cliff faces, roadcuts and local ridges. Although the lack of exposure may have limited the ability to conduct prospecting and soil sampling, other methods can now be applied to the region in order to identify prospective areas beneath the glacial cover.

Geology and Subdivisions of the Creston Formation

The Creston Formation (Schofield, 1915) has been previously divided into three units based on lithology and environment of deposition (Höy, 1993). These three subdivisions (C1, C2 and C3) are considered to be roughly equivalent to the Burke, Revett and St. Regis formations in Montana. On the eastern side of the Purcell Basin, McMechan (1981) further subdivided the Creston into five informal units. Both the upper and lower contacts of the Creston are reported to be gradational (Höy, 1993). Study of the Creston Formation has been relatively limited compared to the more than 86 measured sections and numerous logged drillcores reported from the Burke, Revett and St. Regis formations in Montana and Idaho (Mauk and White, 2004; Boleneus et al., 2005).

An area underlain by the Creston Formation south of Cranbrook, near Yahk Mountain, was chosen for more detailed mapping (Figure 4). The area is considered prospective for sediment-hosted Cu because it contains a significant thickness of middle Creston Formation and hosts a small Cu occurrence, discovered in 2007. The Yahk Mountain area lies on the eastern limb of the Purcell anticlinorium, about 15 km north of the border with Montana. The Creston Formation in this area dips 15–20º east-northeast and is best exposed at higher elevations. For comparative purposes, additional sections of Creston Formation were examined on the east side of Moyie Lake and from drillholes west of Cranbrook. More than 50 samples of Creston sedimentary rocks were collected for future detailed petrographic and geochemical analysis.

The Creston Formation is notable for its alternating units of shallow-water siltstone, argillite, quartzite and silty quartzite. Ripple marks and crossbeds are abundant and consistent with sediment deposition in a relatively shallow, high-energy environment (Figure 5A). Flame structures, load casts, scour surfaces, rip-up clasts and desiccation structures occur locally. Hematite and pyrite also occur locally (Figure 5B), but subhedral to euhedral magnetite is widespread. Magnetic susceptibility readings for the Creston range from 0.1 x 10^{-3} SI units to more than 15 x 10^{-3} SI, with an average of ~4 x 10^{-3} SI. These readings are much higher than those of the other strata in the Purcell Supergroup, which rarely exceed 0.2 x 10^{-3} SI. Metamorphic biotite, muscovite and staurolite occur sporadically and indicate that local conditions may have peaked at middle amphibolite facies.

Basal, middle and upper divisions of the Creston Formations occur in the Yahk Mountain map area and are discussed in detail below. These three subdivisions are roughly the same as those of Höy (1993) and appear to be equivalent to the Burke, Revett and St. Regis formations in Montana:

> The **basal Creston (C1)** is dominated by green-grey siltstone and argillite with rare thin beds of quartzite. Siltite-argillite couplets are common, and a distinctive dark grey to black fissile siltstone occurs. The abundance of syneresis cracks and a lack of desiccation cracks have been cited as evidence that this unit was entirely subaqueous (McMechan, 1981). The Burke Formation in Montana is reported as siltite and argillite that has a range of colours including greenish grey, purple, reddish grey and minor black and grey (Winston and Link, 1993). Several Cu occurrences were noted within the uppermost part of C1 and are described below.
>
> The **middle Creston (C2)** contains interbedded sequences of variably bleached, medium- to thick-bedded siltstone, quartzite and silty quartzite. The base of unit C2 is difficult to constrain; however, the first appearance of thick-bedded white quartzite is used to mark the appearance of the Revett Formation in Montana (Hayes, pers. comm., 2008). The abundance of desiccation cracks in the middle Creston is consistent with repeated subaerial exposure during deposition. Siltstone of the middle Creston is commonly light green, grey or purple. The less abundant quartzite beds within the Yahk Mountain area, when compared to the Troy and Montanore areas of Montana, may be due to limited exposure. The grain size in the middle Creston rarely exceeds a medium sand, consistent with what is described from the majority of the Revett Formation (Boleneus et al., 2005). Much of the Revett has been interpreted to have formed via fluvial braided channels and sheet-flood deposits (Winston and Link, 1993)
>
> The **upper Creston (C3)** resembles the lower Creston in that it is dominated by green, lenticular bedded siltstone and argillite with very few quartzite beds. Siltstone-argillite couplets are common. The stratigraphically equivalent unit in Montana is the St. Regis Formation.

Intrusive Rocks

Although there are relatively few intrusive rocks in the region (Figure 2), coarse-grained gabbro dikes and sills are scattered throughout. A single, poorly exposed gabbro dike cuts the middle Creston in the Yahk Mountain area (Figure 4), but other similar dikes locally cut the Kitchener Formation. A U-Pb zircon crystallization age of 1439 ±2 Ma (Brown and Woodfill, 1998) for a gabbro sill exposed east of Moyie Lake is within error of the U-Pb zircon age of 1443 ±7 Ma (Evans et al., 2000) for rocks equivalent to the Nicol Creek Formation in Montana. Therefore, the gabbro sill is likely part of a feeder system to the overlying Nicol Creek basalts. Another gabbro dike cutting the Kitchener Formation near Cranbrook contains numerous chalcopyrite-rich veins (Hartlaub and Paradis, 2008); however, 'Revett style' Cu deposits have not been linked to any magmatic events.

Stratabound Cu±Ag±Co Potential of the Middle Creston Formation

The mineral potential of an area is commonly related to past discoveries and currently operating mines. By this standard, any Revett-equivalent rocks in the Purcell Basin should be considered to have a high mineral potential despite the lack of significant discoveries in the middle Creston north of the Montana-BC border.

Knowledge of the conditions required to form stratabound copper deposits is important to better understand the mineral potential of the middle Creston. The majority of sediment-hosted stratabound Cu deposits are formed within continental-rift basins due to movement of moderately low pH and oxidized fluids within permeable, shallow-water sedimentary and, more rarely, volcanic rocks (Brown, 1992). Copper, silver, cobalt, lead and other metals are leached from minerals within the sedimentary and/or igneous rocks and carried elsewhere and precipitated. Cox et al. (2007) subdivided sediment-hosted Cu deposits into three groups, based primarily on how Cu precipitates from the fluids. In the reduced-facies deposits, oxidized mineralizing brine interacts with some form of reductant and depos-

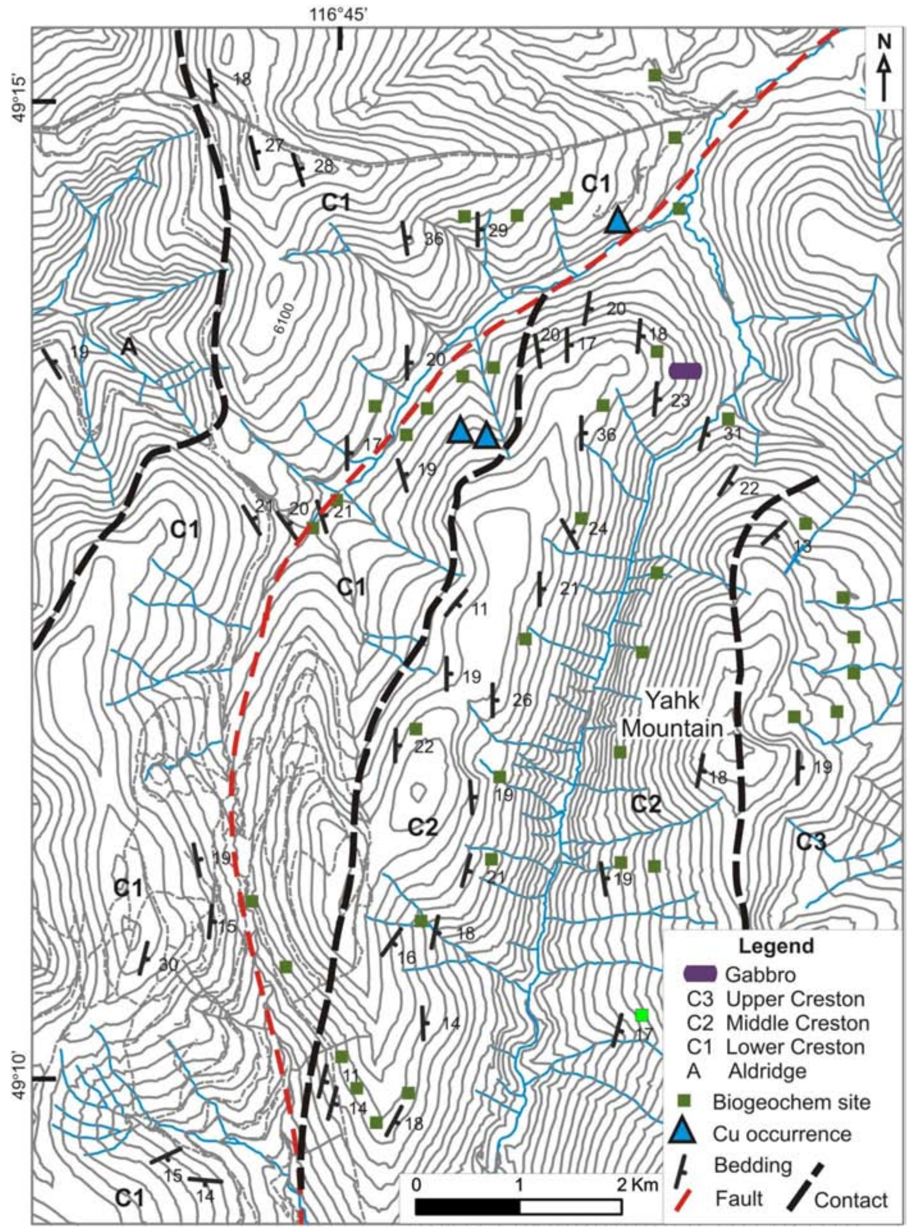

Figure 4. Simplified geology of the Yahk Mountain area south of Cranbrook. Unit descriptions are found in the text. Contour interval is 100 feet. Geological formations in the map area are the Aldridge (A), basal Creston (C1), middle Creston (C2) and upper Creston (C3). See Figure 2 for regional location.

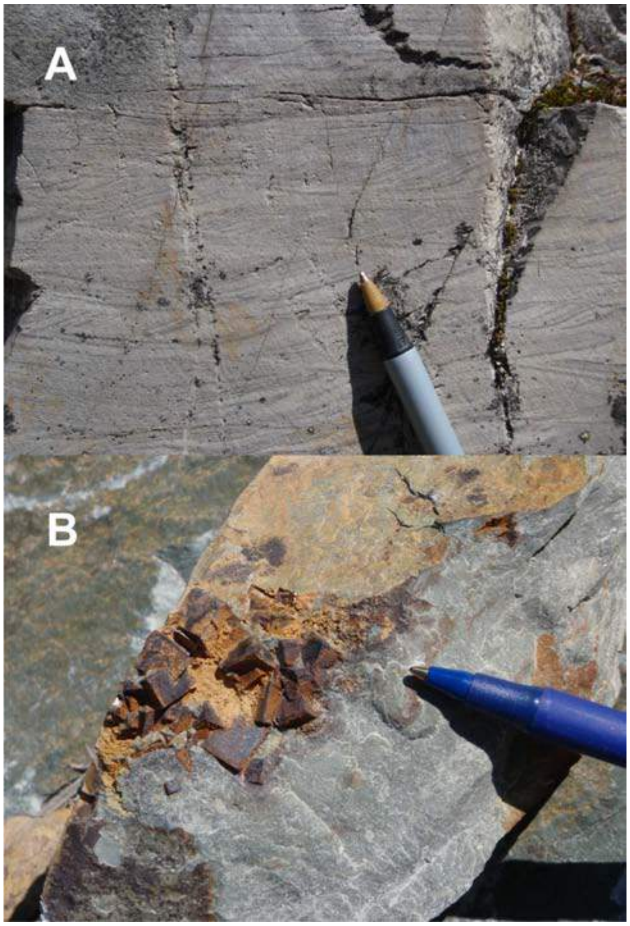

Figure 5. A) Crossbedding in quartzite of the Middle Creston Formation (C2) on Yahk Mountain (UTM Zone 11, 593687E, 5448550N, NAD 83). **B)** Euhedral oxidized pyrite in quartzite of the Creston Formation (UTM 589483, 5465047E).

its Cu±Ag±Co above or lateral to the red-bed sedimentary rocks (Figure 6). This reductant may be a reduced unit, such as black shale, or sulphur derived by bacterial reduction of seawater sulphates (Cailteux et al., 2005). It is the presence of the reductant that can lead to large, high-grade deposits, such as those in the Kupferschiefer and Central Africa. Red-bed–hosted deposits lack or have limited amounts of reducing hostrocks and are typically low grade and small tonnage (Cox et al., 2007). Deposits in the Revett Formation can be viewed as their own subtype, since the known deposits are hosted in quartz-rich sandstone. Unlike the red-bed deposits, however, a reductant in the form of pyritic sand bodies, or possibly hydrocarbon fluids, is believed to have localized Cu and Ag mineralization (Boleneus et al., 2005; Hayes, pers. com., 2008). The control that sedimentary structures locally provide on the distribution of disseminated sulphides is typically cited (e.g., Garlick, 1988; Cailteux et al., 2005) as evidence that Cu mineralization occurred prior to compaction and lithification of sediments. For example, sulphides may occur within troughs of ripples and ore may show signs of sedimentary deformation, such as slumping or compaction (Garlick, 1988).

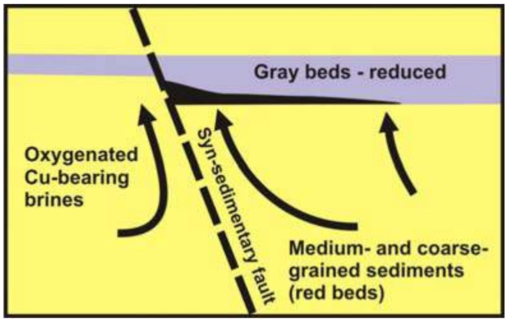

Figure 6. Typical model for the formation of sediment-hosted stratabound Cu deposits. The scale of the mineralizing system can vary from local to district.

Several key points from the deposit models indicate the characteristics important to stratabound Cu±Ag±Co exploration in the Purcell Basin:

- relatively thick units of oxidized, shallow-water sediments
- evidence for movement of brines through these oxidized sediments
- evidence for local precipitation of disseminated sulphides along early sedimentary structures

The Yahk Mountain area (Figure 4) encompasses all three of these important factors. Evidence for large-scale movement of oxidized fluids is noted within the area as scattered exposures of spectacular purple and red hematite mottling along bedding planes and fractures (Figure 7A) that occur immediately south and east of Cu mineralization. A similar style of alteration occurs within the Kupferschiefer sediment-hosted Cu deposits in Poland (Cox et al., 2007) and may mark the location of a localized redox front. Manganese minerals were noted on many fracture and joint surfaces in the same area (Figure 7B). However, this alteration process may be related to a later event. Boleneus et al. (2005) indicated that a lavender shade to the sedimentary rocks is occasionally apparent above and below, but not within, the prospective horizons of the Revett Formation.

In 2007, a new occurrence of disseminated Cu sulphides was discovered within the Creston Formation along the Tepee Creek forestry road (Hartlaub and Paradis, 2008; UTM 593577E, 5454607N). The new showing, named ‘Tepee Creek’, consists of green argillite containing fine bornite and chalcopyrite disseminated along the bedding planes. Minor amounts of green copper oxidation mark the discovery outcrop, and two grab samples returned assay results with Cu (564 and 2086 ppm) and Ag (2 and 6 ppm) values (Hartlaub and Paradis, 2008). In 2008, a 30 m section of outcrops along a forestry road was discovered to contain trace amounts of disseminated malachite and chalcopyrite in siltstone (UTM 592315E, 5452924N). Assay analyses for samples from this location are underway. Although these Cu showings do not occur within quartzite, Cu occurrences have been reported from both fine and course units of the Burke, Revett and St. Regis formations (Boleneus et al., 2005). Along the east side of Moyie Lake, there are several locations where crosscutting quartz and quartz-carbonate veins and breccias contain copper sulphides (Figure 8A–C). This copper mineralization postdates stratabound mineralization and may indicate later remobilization of metals.

Key Exploration Strategies

Having identified a reasonable potential for sediment-hosted, stratabound Cu±Ag±Co mineralization on the Canadian side of the Belt-Purcell Basin, it is useful to note some of the key strategies that may be utilized for future exploration in the region. These exploration strategies were gleaned by examining the literature and visiting the sediment-hosted stratabound Cu deposits of Montana.

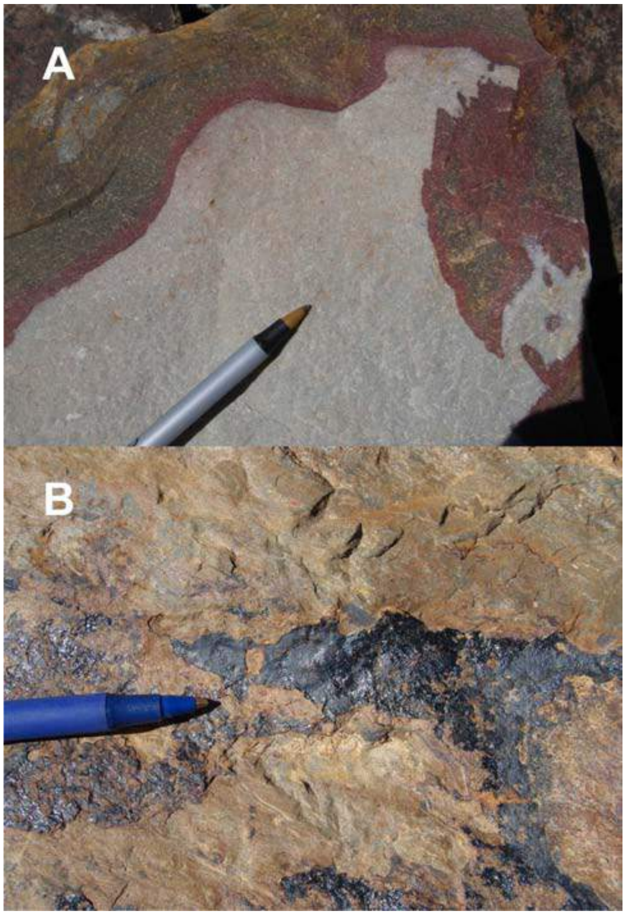

Figure 7. A) Red and purple iron-oxide alteration patterns within sandstone of the middle Creston Formation (UTM Zone 11, 594161E, 5453650N, NAD 83). This alteration is especially striking due to the white bleaching (argillic alteration) of the rock. Bleaching may indicate leaching of Cu and other metals from the rock, as has been seen in the Revett Formation. **B)** Manganese oxide, likely pyrolusite, on a joint surface (UTM 594038E, 5453531N).

Stream and biogeochemical sampling: Prospecting stream geochemical anomalies led to initial discoveries at most of the stratabound Cu deposits in Montana (Hayes, pers. comm., 2008). Although a BC Geological Survey database of regional stream sampling exists, a more detailed study will need to be carried out in selected parts of the Creston Formation outcrop area.

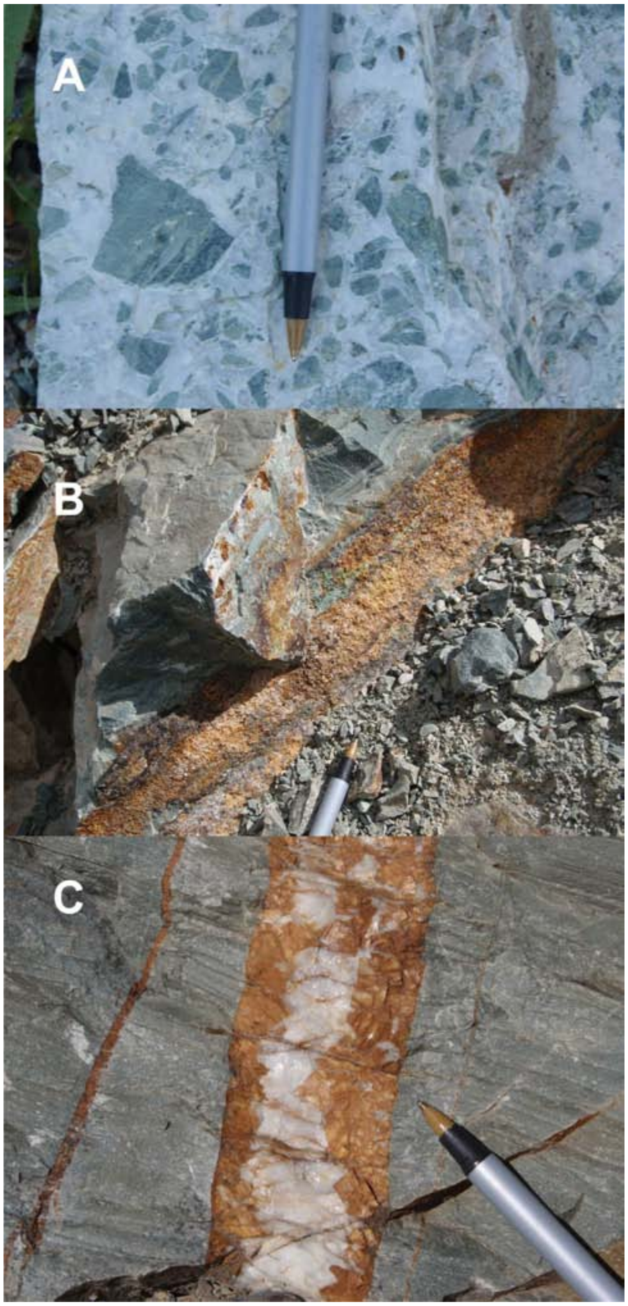

Figure 8. A) Breccia composed of siltstone-argillite clasts in a quartz vein matrix. The breccia locally contains chalcopyrite and is exposed in a roadcut on the east side of Moyie Lake (UTM Zone 11, 585407E, 5466634N, NAD 83). **B)** Quartz, iron carbonate, chalcopyrite and malachite cementing joint surfaces in the Creston Formation (UTM 585475E, 5467010N). **C)** Silty quartzite and argillite from the middle Creston Formation cut by a quartz-carbonate vein (UTM 585059E, 5464231N).

Biogeochemical sampling may also help provide targets in areas of poor exposure.

Tracing of prospective strata: Several of the deposits in Montana were discovered by a simple strategy of exploring along prospective stratigraphic horizons after traces of mineralization had been discovered (Hayes, pers. comm., 2008). Thick-bedded quartzite is the typical hostrock for the Revett deposits of Montana (Figure 9A), but the finer grained sedimentary rocks should not be ruled out. The disseminated nature of the mineralization is not always apparent, especially where limonite has partially replaced chalcopyrite (Figure 9B, C).

Induced-polarization surveys: Despite the low of concentration of sulphides, stratabound Cu deposits should produce IP anomalies due to the otherwise restricted presence of sulphides and graphite within the Creston Formation.

Aeromagnetic mapping: The abundance of magnetite within the Creston Formation indicates that detailed aeromagnetic imagery would be useful for tracing contacts in areas of poor exposure. A full evaluation of magnetic susceptibility measurements collected in 2008 has not yet been completed; however, initial results indicate that both mineralized and nonmineralized Creston Formation rocks have similar magnetic susceptibility values.

Future Products and Research Directions

Release of a GIS map dataset including outcrop locations, lithological interpretations, structural measurements, magnetic-susceptibility measurements and georeferenced photos

Publication of measured sections from prospective areas of the middle and upper Purcell Supergroup; lithological descriptions will be further constrained by petrographic analysis of reference samples

Public release of the complete biogeochemical and lithogeochemical database

Publication of new geochronological data

Completion of fluid inclusion studies on mineralized quartz veins from the Creston and Sheppard formations; this study will be completed in order to constrain the temperature and chemistry of mineralizing fluids

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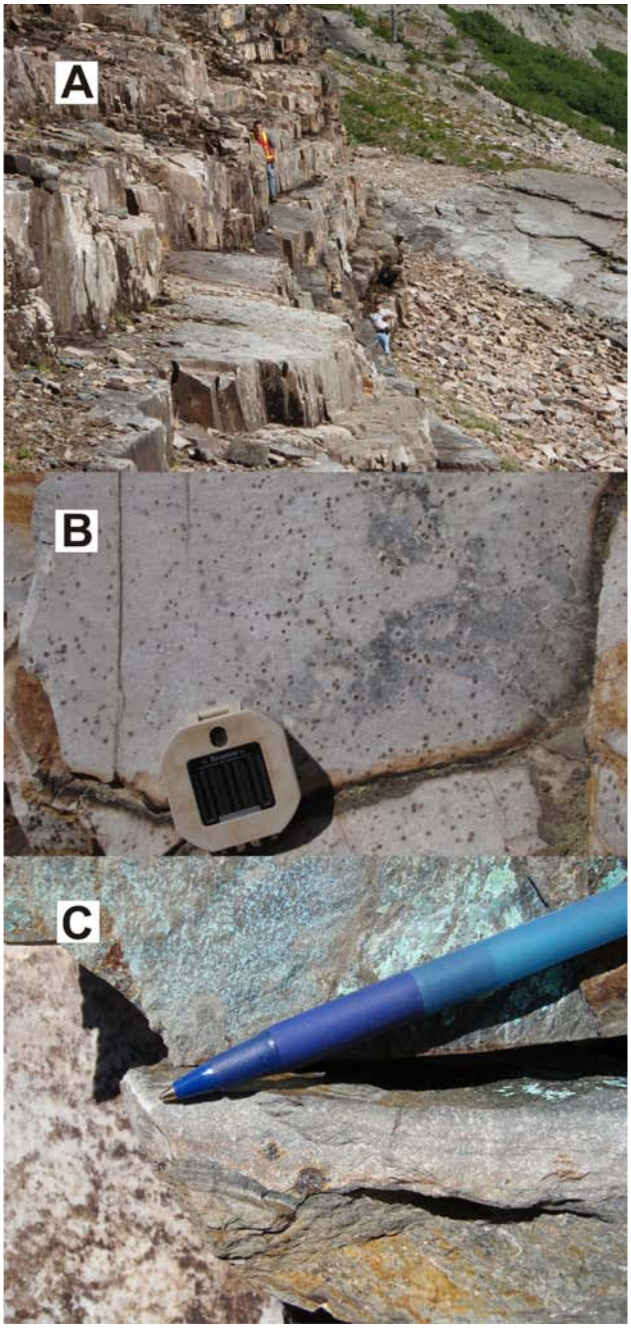

Figure 9. A) Thick-bedded quartzite of the lower Revett Formation. **B)** Limonite spots replacing chalcopyrite in lower Revett Formation quartzite. **C)** Detail of limonite spots replacing chalcopyrite and chrysocolla alteration. All three photos were taken at exposures of the Montanore deposit on the north shore of Rock Lake, Montana.

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