The characteristics, origin and exploration potential for sediment-hosted Cu±Ag mineralization in the Purcell Supergroup, Canada

R.P. Hartlaub[1], W.J. Davis[2], and C.E. Dunn[3]

[1] Department of Mining and Mineral Exploration, British Columbia Institute of Technology, Burnaby, BC, russell_hartlaub@bcit.ca
[2] Natural Resources Canada, Ottawa, ON
[3] Consulting Geochemist, Sidney, BC

December, 2011

Geoscience BC Report 2011-16

INTRODUCTION

Large cratonic basins filled with immature siliciclastic sediments are excellent source regions for sediment-hosted copper deposits (Hitzman, 2000). The Mesoproterozoic Belt-Purcell basin (Fig. 1) has sedimentary rock thickness of at least 19 km within the central part of the basin in BC (Cook and van der Velden, 1995) and up to 18 km in the U.S. (Winston and Link, 1993). This large thickness of sediment was deposited in a relatively rapid period (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 Troy, Rock Creek and Montanore, are all located in western Montana; however, evidence for sediment-hosted copper mineralization has recently been identified in southeastern British Columbia (Hartlaub and Paradis, 2008; Hartlaub, 2009).

The majority of sediment-hosted stratabound Cu deposits are formed within continental rift basins due to movement of moderately low pH 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, carried through aquifers and precipitated. Syn-sedimentary faults may provide convenient conduits for the movement of mineralizing fluids (Mauk et al. 1992). Cox et al. (2007) subdivided sediment-hosted copper deposits into three groups based, primarily, on how copper precipitates from the fluids. In the first group, reduced facies deposits, oxidized mineralizing brine interacts with some form of reductant and deposits Cu±Ag±Co above or lateral to the “redbed” sediments. This reductant may be a reduced unit, such as black shale, or sulphur derived by bacterial reduction of seawater sulphates (Mauk and Heishima, 1992; Cailteaux et al., 2005). The second group, redbed hosted deposits, lack or have limited amounts of reducing host rocks and are typically low grade and small tonnage (Cox et al., 2007). Deposits in the Revett Formation can be viewed a seperate sub-type since the known deposits are hosted in quartz-rich sandstone. Unlike the redbed deposits, a reductant in the form of pyritic sand bodies, or possibly hydrocarbon fluids, is believed to have localized copper and silver

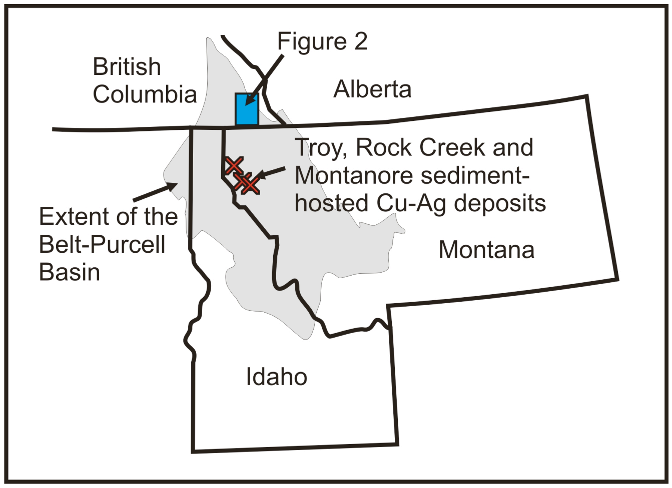

Figure 1. Approximate extent of the exposed Belt-Purcell basin in British Columbia, Montana, Idaho and Washington. (Purcell basin in Canada and the Belt basin in the United States). The location of the study area (shown by the rectangle) and known sediment-hosted Cu deposits are also shown.

mineralization (Boleneus et al., 2005; Hayes, pers. com., 2008). For all these groups, the control that sedimentary structures locally provide on the distribution of disseminated sulfides is typically cited as evidence that Cu mineralization occurred prior to compaction and lithification of sediments (e.g., Garlick, 1988; Cailteaux et al., 2005). For example, sulfides may occur within troughs of ripples and ore may show signs of sedimentary deformation such as slumping or compaction (Garlick, 1988).

Several sediment-hosted copper occurrences from the Cranbrook area (Fig. 2) were examined in detail and are described below. U-Pb geochronology samples were collected in order to better constrain the age of these mineral occurrences. An important factor limiting exploration and development in the area is the limited bedrock exposure due to thick deposits of glacial drift. Fifty samples of lodgepole pine bark were collected to test biogeochemical exploration for concealed mineralization.

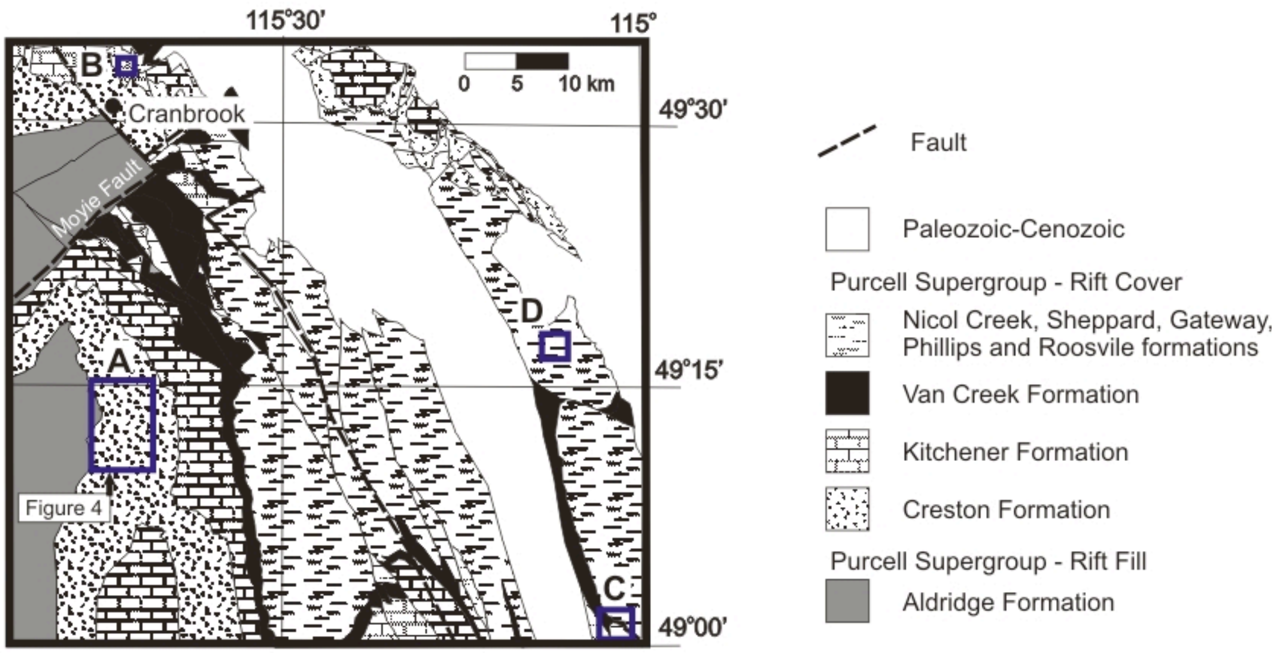

Figure 2. Simplified geology of Purcell basin in the Cranbrook area (modified from Höy et al., 1995); A, Tepee Creek area; B, The King occurrence; C, The Roo occurences; D, Sheep Mountain area.

REGIONAL GEOLOGY

Seminal reports by Höy (1985, 1993) provide a structural and stratigraphic framework for the Belt-Purcell basin in southeastern B.C. (Fig. 2). The oldest rocks of the Purcell Supergroup are exposed along the core and western margin of a large north-northwest trending anticlinorium. Regional compression during the Jurassic-Early Cretaceous and again during the Late Cretaceous-Paleocene transported the basin east and northeastwards (Price and Sears, 2000). The base of the Canadian portion of the basin, south and east of Cranbrook, contains up to 12 km thicknesses of rift-fill turbiditic rocks (Lydon, 2007). These "rift-fill" rocks, the Aldridge Formation, host the world-class Sullivan SEDEX Zn-Pb deposit. The Moyie sills, a voluminous series of mafic intrusive rocks, cut the Aldridge Formation but are believed to be syn-depositional. A U-Pb crystallization age of 1468 ± 2 Ma for a Moyie sill establishes the age of the Aldridge Formation (Anderson and Davis, 1995). Although the majority of research in the region has focused on the Aldridge Formation, the Sullivan deposit, and the Moyie sills, several detailed stratigraphic studies have also been completed on the overlying rocks of the Purcell basin. For example, McMechan (1981) developed a lithostratigraphic correlation chart for the northern Belt-Purcell Basin and Gardner and Johnston (2007) refined the stratigraphy of the upper Purcell Supergroup. The Creston Formation (Fig. 2) represents the beginning of the "rift-cover" sequence (Lydon, 2007). Unlike the Aldridge Formation, the Creston Formation contains abundant magnetite and is easily traceable on aeromagnetic maps (Fig. 3). The Creston Formation in the study area can be subdivided into basal, middle, and upper divisions. These three subdivisions (Höy, 1993), appear to be equivalent to the Burke, Revett, and St. Regis formations in Montana. Elsewhere, on the eastern side of the Purcell Basin, five informal units have been identified (McMechan, 1981). At Moyie Lake the measured thickness of the Creston Formation is just over two kilometers (Höy, 1985). Both the upper and lower contacts of the Creston are reported to be gradational (Höy, 1993). The formation is notable for alternating units of shallow-water siltstone, argillite, quartzite, and silty quartzite. Ripple marks, desiccation cracks and cross-beds are abundant and consistent with sediment deposition in a relatively shallow, high-energy environment. Flame structures, load casts, scour surfaces and rip-up clasts are present locally. Magnetic susceptibility readings for the Creston Formation range from 0.1 $x10^{-3}$ SI to more than $15x10^{-3}$ SI, with an average of approximately $4x10^{-3}$ SI. These readings are much higher than other strata of the Pucell Supergroup, where readings rarely exceed $0.2x10^{-3}$ SI units.

Overlying the Creston is the Kitchener Formation, a distinctive horizon of carbonate rocks that include oolitic limestone and dolomitic siltstone (Höy, 1993) that has been correlated with the Empire and Helena formations in western Montana (Winston, 1986). Above the Kitchener, maroon to green siltstone and argillite of the Van Creek Formation predates eruption of flood basalts of the Nicol Creek Formation (McMechan et al. 1980). The Nicol Creek Formation provides an important marker horizon within the basin and is indirectly dated by a 1443 ± 7 Ma porphyritic rhyolite from the equivalent Purcell lavas in Montana (Evans et al., 2000). Overlying the Nicol Creek Formation are coarse clastic and stromatolitic carbonate rocks of the Sheppard Formation. In the northern Purcell basin, the Sheppard Formation is overlain by fine-grained, shallow-water clastic rocks of the Gateway, Phillips and Roosville formations

(Gardner and Johnston, 2007). The shallow-water nature of these units is clearly indicated by an abundance of ripple marks, desiccation cracks and salt casts (Hartlaub and Paradis, 2008). Salt casts, especially abundant in the Gateway Formation, occur in the stratigraphically equivalent Mt. Shields Formation in Montana (O'Brien, 1968).

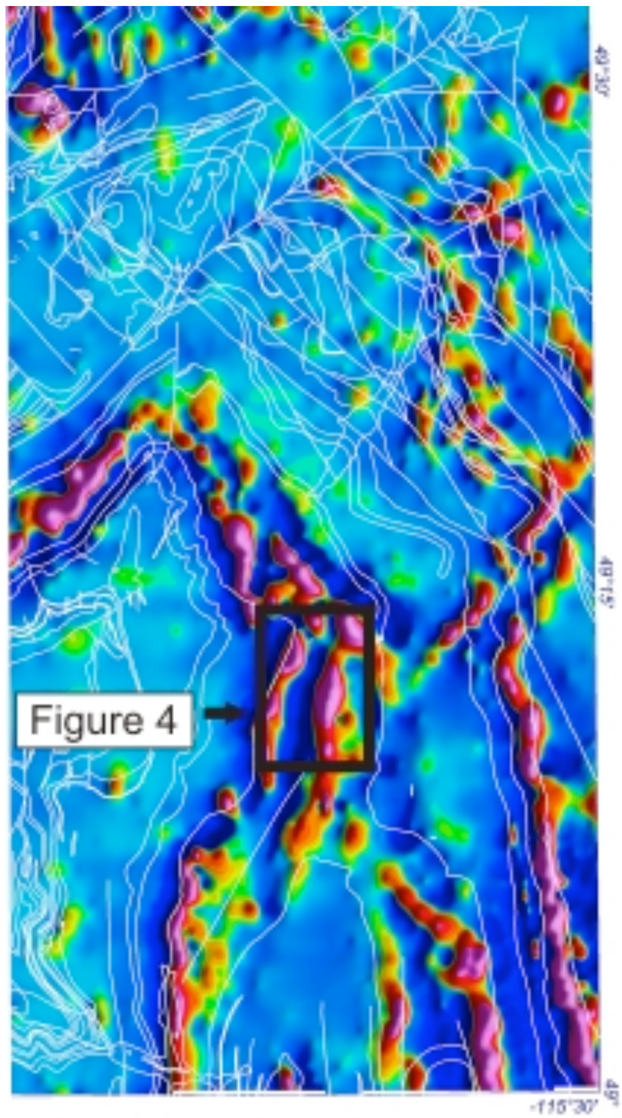

Figure 3. Vertical gradient airborne magnetic map of the western half of figure 2 (Canadian Aeromagnetic Data Base). Regional geological contacts and faults, as well as the Tepee Creek Area (Fig. 4) are indicated. An abundance of magnetite in the Creston Formation makes it an easily traceable magnetic high.

SEDIMENT-HOSTED COPPER OCCURRENCES

Sediment-hosted copper mineralization in the Canadian portion of the Belt-Purcell Basin appears to exist in at least four different settings (Fig. 2):

1) Occurrences of sediment-hosted stratabound Cu-Ag mineralization were identified within the Creston Formation south of Cranbrook (Tepee Creek area - Hartlaub and Paradis, 2008; Hartlaub, 2009). These mineral occurrences are deemed to be of special importance as they lie within the approximate stratigraphic equivalent of the Revett Formation.
2) A coarse-grained gabbro dike containing numerous quartz-chalcopyrite veins is exposed near Eager Hill north of Cranbrook (the King occurrence). A significant zone of alteration and disseminated Cu mineralization occurs in host rocks of the Kitchener Formation.
3) Coarse clastic rocks of the Sheppard Formation on the Roo Property, southeast of Cranbrook, contain mineralized intersections with Cu grades up to 1.8% (Thomson, 1990). These mineralized, coarse clastic rocks are spatially associated with gabbro sills and basalts of the Nicol Creek Formation.
4) Numerous disseminated and fracture controlled Cu-polymetallic occurrences occur on and adjacent to Sheep Mountain**.** Although sediment-hosted, these occurrences appear to be genetically associated with a series of K-feldspar megacrystic syenite sills.

The Tepee Creek occurrences - Sediment-hosted stratabound Cu-Ag in the middle Creston Formation

A series of new Cu occurrences were discovered in 2008 and 2009 within a very poorly exposed section of the Creston Formation near Tepee Creek (Fig. 4). Variable amounts of green Cu oxides mark these occurrences. The showings consist of green argillite containing fine-grained bornite and chalcopyrite distributed along bedding planes and chrysocolla coatings on weathered surfaces. Two grab samples returned assay results with elevated Cu (564 and 2086 ppm) and Ag (2 and 6 ppm) (Hartlaub and Paradis, 2008; Hartlaub, 2009). The showings lie 1 to 2 kilometers southeast of the Silver Pipe occurrence, a gossanous vein system with elevated Pb, Ag and Cu values (Yeager and Ikona, 1982).

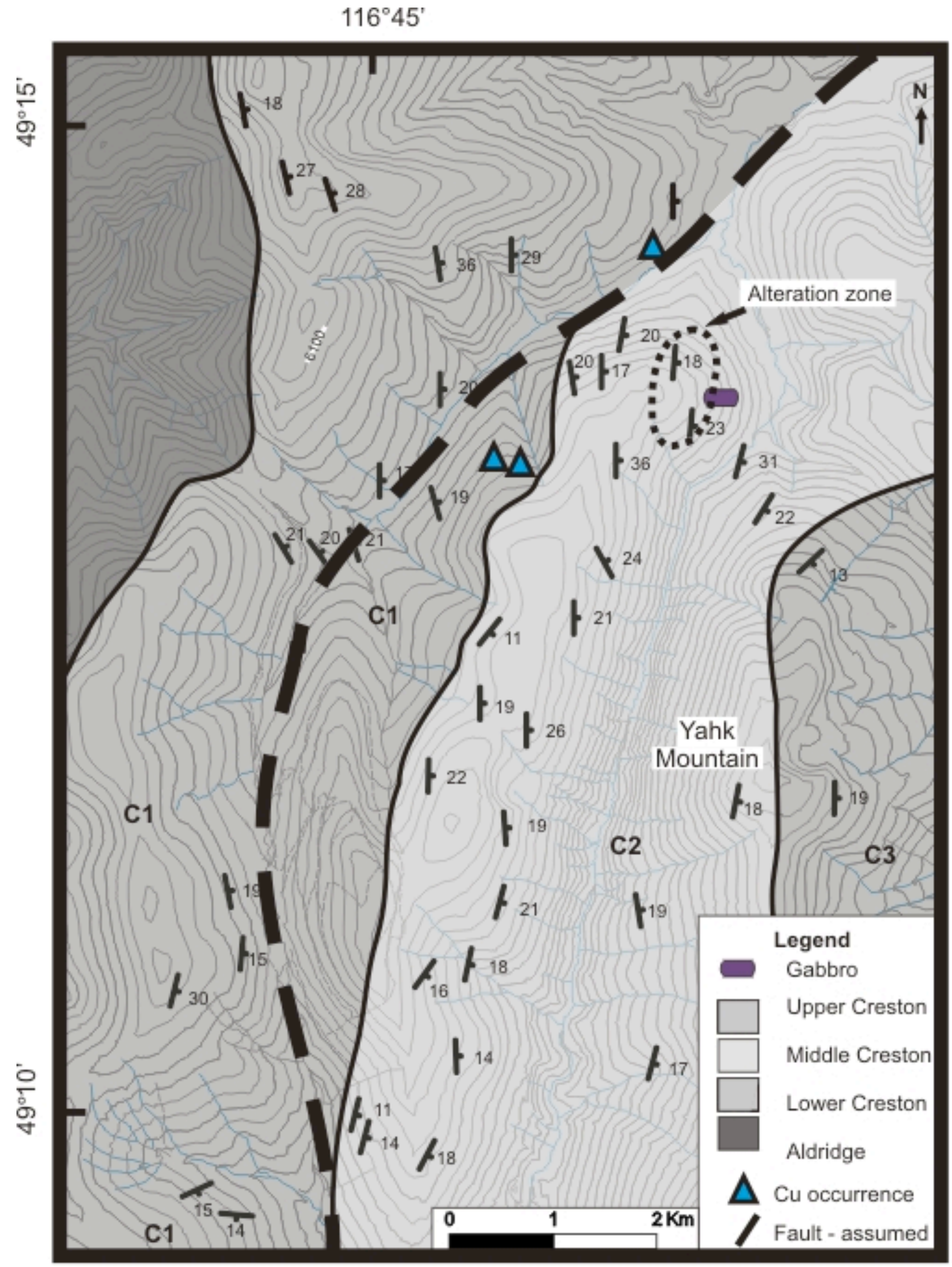

Figure 4. Simplified geological map of the Yahk Mountain area, south of Cranbrook, B.C. Tepee Creek Cu occurrences and alteration zones are identified. Unit descriptions are found in the text. Contour interval is 100 feet. Geological formations in the map area are the Aldridge(A), basal Creston (C1), middle Creston (C2) and upper Creston (C3). See fig. 2 and 3 for regional location.

In the Tepee Creek area the basal Creston (C1) is dominated by green-grey siltstone and argillite with rare thin beds of quartzite. Siltstone-argillite couplets are common and a distinctive dark grey to black fissile siltstone is present. 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 middle Creston (C2) in this area contains interbedded sequences of variably bleached medium to thick-bedded siltstone, quartzite and silty quartzite with local crossbedding (Fig. 5a). The abundance of desiccation cracks in the middle Creston is consistent with repeated subaerial exposure during deposition (Fig. 5b). Siltstone of the middle Creston is commonly light green, grey or purple in color. The overall grain size of the middle Creston rarely exceeds that of a medium sand, consistent with descriptions of the Revett Formation (Mauk and White, 2004; Boleneus et al., 2005). Much of the Revett is 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 few quartzite beds. Siltstone-argillite couplets are common. The stratigraphically equivalent unit in Montana is the St. Regis Formation.

A significant alteration zone is exposed about 1 km south and southeast of the Tepee Creek copper occurrences. In this area, spectacular purple and red hematite mottling is indicative of oxidized fluid movement through the medium grained sandstone (Fig. 5c, d). Manganese oxides are also visible on many of the bedding planes and on some fracture surfaces. Such red-bed style alteration is also reported at the Kupferschiefer deposits in Poland and Germany (Cox et al., 2007), and is a common feature of many other sediment-hosted stratiform copper deposits (Brown, 2005). This red-bed alteration is important as the location of the redox front may be critical for identifying potential ore zones.

The presence of magnetite or pyrite may be helpful in identifying reduced units that are prospective for Cu deposition. The Silver Pipe Pb-Ag-Cu occurrence, 1 to 2 km northwest of the Cu occurrences and also hosted in the Creston Formation, may represent an outer zone of mineralization similar to the galena-calcite zone (Mauk and White, 2004) at the Troy mine in Montana. A small exposure of mafic intrusive rock is situated at the eastern margin of the alteration zone (Fig. 4). The extremely poor level of outcrop exposure in the area (<1%) makes surface tracing of prospective stratigraphic horizons impossible. Geophysical, geochemical, and biogeochemical methods are all cited as means to explore beneath extensive areas of glacial cover. Samples of lodgepole pine bark were collected throughout the Tepee Creek area to test the usefulness of biogeochemical sampling for exploration in the area.

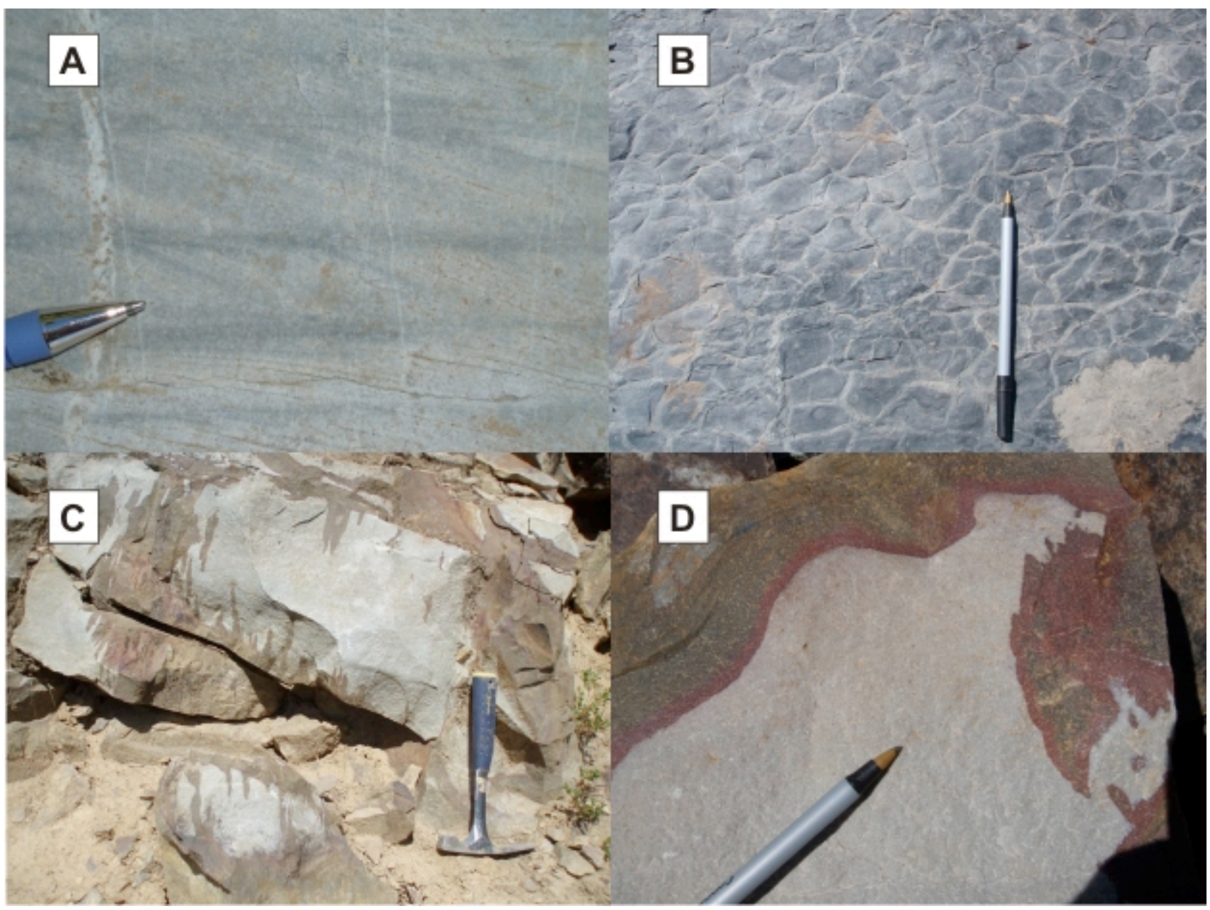

Figure 5. A: Cross-bedding in quartzite of the middle Creston on Yahk Mountain; B: Well developed desiccation cracks in siltstone of the lower Creston formation in the Yahk Mountain area; C and D: Red and purple iron-oxide alteration patterns within sandstone from the middle Creston Formation. This alteration is especially striking due to the white bleaching (argillic alteration) of the rock. The alteration is exposed approximately 1 km south and east of the Tepee Creek Cu occurrences.

The King occurrence - Sediment-hosted Cu associated with mafic intrusive rocks

A significant number of cupriferous polymetallic occurrences associated with mafic sills and dikes are found within the Cranbrook area. A large proportion of these showings occur where Moyie sills cut the middle Aldridge Formation. The Moyie sills have been interpreted to be roughly syn-depositional, with intrusion and crystallization occurring prior to lithification of the surrounding sediments (Höy, 1993). Although the Moyie sills are a voluminous component of the Aldridge Formation, there are a significant number of mafic sills and dikes that cut the Creston, Kitchener and Van Creek formations. These dikes have been postulated to be feeders to flood basalts of the Nicol Creek Formation. A 1439 ± 2Ma age (Brown and Woodfill, 1998) for a gabbro sill that cuts the Kitchener Formation is within error of the 1443 ± 7 Ma (Evans et al., 2000) age for Purcell lava in Montana.

The King occurrence, first reported in a Geological Survey of Canada Memoir by Schofield (1915), is located 8 km north of Cranbrook. At this site a number of roughly northeast-striking gabbroic intrusions cut carbonaceous fine-grained clastic rocks of the Kitchener Formation. Past exploration work identified large soil geochemical anomalies and a mineralized gabbro. A 400m diamond drill program in 2005 intersected copper-bearing gabbro in two holes across an average thickness of 35 meters (Walker, 2005). In addition to mineralization within the gabbro, the surrounding Kitchener Formation contains significant disseminated chalcopyrite.

The Roo occurrences - Red-bed copper associated with the Nicol Creek-Sheppard Formation unconformity

The Roo property (Fig. 2) is located within the Galton Range of the Rocky Mountains near the Montana border. At this location, the Nicol Creek Formation is well exposed and is unconformably overlain by sandstone, conglomerate, and stromatolitic carbonate rocks of the Sheppard Formation. The Nicol Creek Formation consists of a distinctive flood basalt unit within the dominantly siliciclastic Belt-

Purcell Supergroup. In the United States, the Nicol Creek Formation, is termed the “Purcell lava” and is best exposed and studied in Glacier National Park, Montana (McGimsey, 1985). The Purcell lava is commonly used as a marker horizon within the basin due to its distinctive nature and relatively widespread occurrence. The Nicol Creek Formation is dominated by vesicular and amygdaloidal flows. Vesicles and gas chambers locally provide well-defined top indicators to the flows. Plagioclase-porphyritic flows are also relatively common and are typically interlayered with the vesicular lavas. Höy (1993) provides several measured sections of the Nicol Creek Formation and reports that, although thin pillowed horizons exist in rare locations, the majority of the volcanics appear to be subaerial in nature. A subaerial setting may be important, as reduced sulfur in marine volcanic rocks may preclude formation of a hematite-stable environment where Cu may be leached from the rocks (Cox et al., 2007). Volcaniclastic rocks and layered tuffs occur, but are relatively thin beds compared to the thick basalt flows. The Nicol Creek basalts have not been dated, in large part due to a general lack of zircon in mafic extrusive rocks. However, a regionally restricted rhyolite to quartz latite flow yielded a 1443 ±7 Ma age from the Purcell lavas in Montana (Evans et al., 2000). A 1439 ± 2 Ma age (Brown and Woodfill, 1998) for a gabbro sill that cuts the Kitchener Formation indicates that these gabbros are probable feeder dikes to the overlying Nicol Creek basalts.

The Sheppard Formation directly overlies volcanic rocks of the Nicol Creek Formation, and is distinctive due to the local presence of well-developed stromatolitic rocks within the section. Interlayered siltstone, quartz arenite, conglomerate and oolitic carbonate rocks make up the remainder of the Sheppard Formation. An unconformable relationship between the Sheppard and Nicol Creek formations has been suggested due to locally missing (eroded?) Nicol Creek strata and the presence of conglomerate at the base of the Sheppard Formation (Höy, 1993).

Initial unpublished discoveries of mineralization at the Roo Property occurred as early as 1902, with numerous shallow shafts developed to follow vein hosted copper. A barite vein up to 1.5 m wide was locally mined for barite in 1940. More recent exploration work was completed by Cominco Ltd. in 1967. Drilling by Teck Exploration Ltd. in 1989 encountered numerous 1 to 5 m thick mineralized intersections with Cu grades up to 1.8% (Thomson, 1990). The majority of copper mineralization was reported as hosted in quartzo-feldspathic greywacke and conglomerates of the Sheppard Formation, mainly as fracture coatings of malachite and chalcocite. The mineralization was thought to be related to dissolution and redeposition of metals from the Nicol Creek volcanics by groundwater movement (Thomson, 1990). Three follow-up diamond drill holes by Noranda Inc. in 1993 intersected minor copper mineralization, but three of six additional holes by Ruby Red Resources in 2008 intersected significant copper-cobalt grades. The 1993 drill holes by Noranda were reexamined by the first author in an attempt to better characterize the mineralization. Of particular interest is a vertical hole (R93-11) that cuts the sub-horizontal strata at the Roo Property. The upper 64 meters of the hole passes through interlayered quartzite, stromatolites, oolitic limestone, and siltstone (Fig. 6a). A two meter section of mafic volcanic rock appears to mark a transition between the fine clastic and carbonate rocks above, and coarse clastic carbonate rocks below (Fig. 6b). Interlayered arkosic and conglomeratic rocks containing numerous quartz-carbonate-barite veins occur beneath the volcanic flow. Some thin veins contain visible pyrite-chalcopyrite (Fig. 6c). The bottom 3 meters of the hole (132-135m) contains amygdaloidal basalt of the Nicol Creek Formation. Although the Nicol Creek Formation does contain disseminated chalcopyrite, best mineralization occurs in the accompanying veins and disseminated in the adjacent coarse clastic rocks (Fig 6d). Propylitic and sericitic alteration of the volcanic rocks was locally noted. A highly altered stratigraphic unit containing abundant barite, both in the matrix and as large random crystals, is interpreted as a barite-cemented sandstone. Barite cementing of sedimentary rocks, common within hydrothermal sinters, appears consistent with the local quartz and barite veining, alteration, and elevated cobalt values. The abundance of overlying stromatolites may also be evidence of an active hydrothermal system, as described by Canet et al. (2005). Together, most evidence suggests that this mineral occurrence, although sediment-hosted, is related to hydrothermal activity associated with the mafic magmatism that created the Nicol Creek Formation.

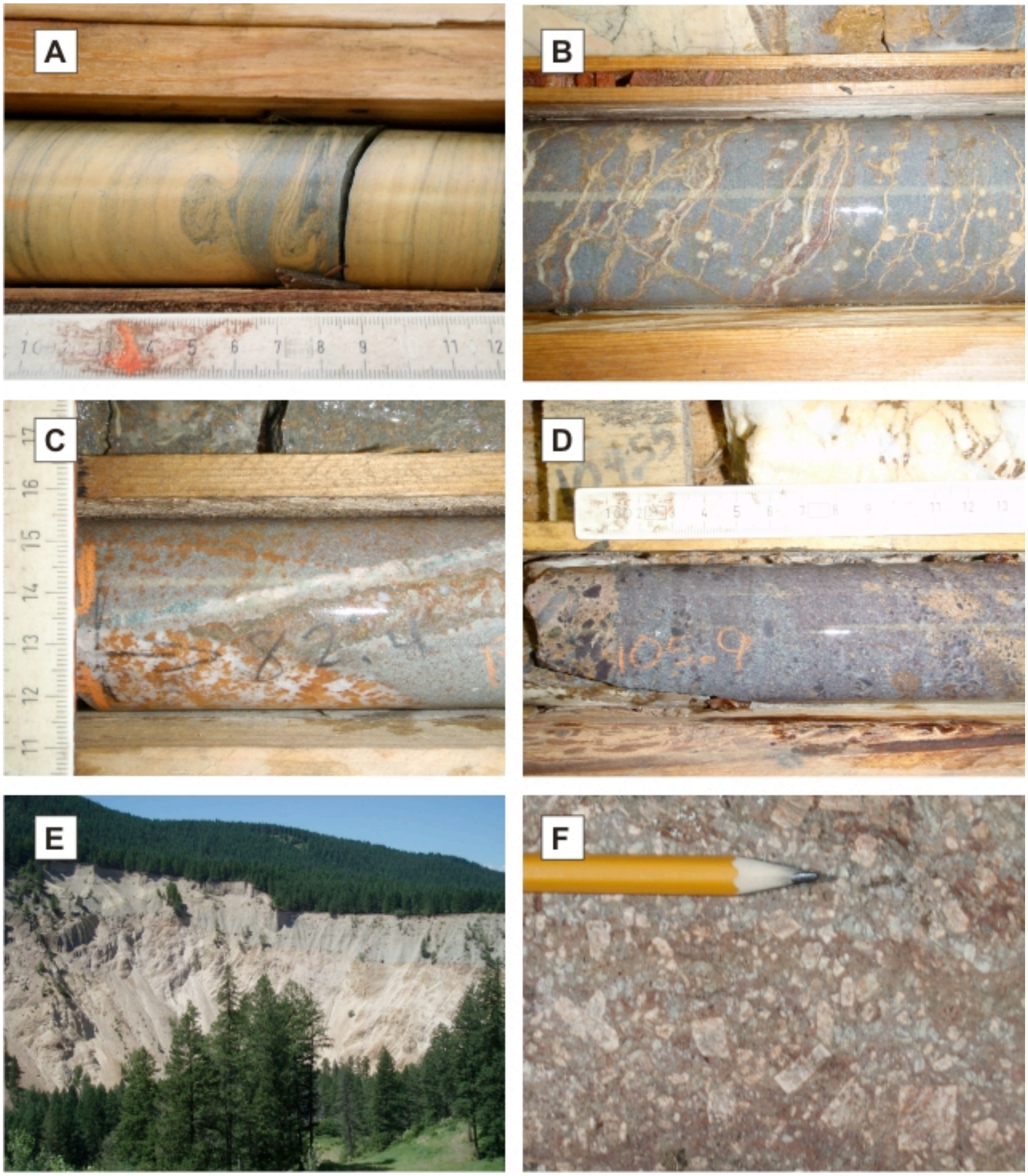

Figure 6. A: Stromatolite from 22m in hole R93-11; B: Barite-veined mafic volcanic rock of the Nicol Creek Formation at 64m in hole R93-11. This unit marks the transition from fine clastic and carbonate rocks (above) to coarse clastic rocks (below); C: Chalcopyrite-pyrite bearing vein cut by a younger, non-mineralized, quartz-carbonate vein at 82m in hole R93-11; D: Lavender lithic arenite grit from 106m in hole R93-11. This clastic contains angular clasts of mafic volcanic; E: An approximately 100 m high cliff face on the west side of the Elk River, at Sheep Mountain. The thick (≥15m) layer of glacial drift that is exposed at the top of the cliff is typical of much of the Cranbrook area. The underlying Purcell Supergroup rocks have undergone significant argillic alteration; F: K-feldpar porphyritic syenite sill that is exposed on Sheep mountain.

The Sheep Mountain occurrences – Intrusion-related copper-polymetallic mineralization

Numerous sediment-hosted copper showings have been reported in the Sheep Mountain area east of Cranbrook (Fig. 2; BC MINFILE 82GSW010, 011, 012, and 028). These mineral occurrences, including the Ramshorn, Jennie, Sweet May, and Silver King, consist of disseminated and fracture-controlled sulfides. A thick apron (>50 m) of glacial drift (Fig. 6e) covers much of the area but rare bedrock exposures and exploration trenches expose sections of deformed and altered dolostone and siltstone assigned to the Roosville Formation. Quartz arenite of unknown affinity is also locally exposed. These sedimentary rocks are cut by one or more 10 m-thick syenite sills with well-developed K-feldspar phenocrysts (Fig. 6f). Both the sills and the surrounding sedimentary rock have been strongly altered. The alteration shell extends sporadically for at least a kilometer in every direction and includes intense carbonate, argillic and sericitic alteration that replaced original minerals with clay, sericite, calcite, quartz and pyrite. Amphibole phenocrysts within the syenite have been completely replaced with a combination of calcite, chlorite, and iron oxides. Rare copper-bearing quartz stockwork and quartz-carbonate veins occur throughout the area. One major Cu-bearing vein strikes approximately 060° and dips steeply southeast. Some disseminated and fracture controlled copper mineralization also exists in the area. Chalcopyrite and bornite are the main sulfides with malachite and azurite also present. Significant iron-oxide alteration was noted within angular float on the west side of Sheep Mountain.

The coincidence of the syenite intusion, alteration zone, and disseminated- and vein-controlled copper mineralization fits a hydrothermal porphyry-type system rather than a low-temperature strata-bound copper genetic model. Given that both the intrusion and the mineralized veins crosscut the stratigraphy, they must be younger than the Roosville Formation. A group of Cretaceous alkaline K-feldspar porphyritic plutons, termed the Howell Creek suite, occurs 30 to 40 km to the east. These intrusions are associated with low-grade, disseminated gold mineralization (Barnes, 2002).

GEOCHRONOLOGY

Two samples were collected for U-Pb analysis by sensitive high-resolution ion microprobe (SHRIMP). A sample of Nicol Creek interflow sediment was collected in order to better constrain the age of Nicol Creek magmatism in the Cranbrook area. A second sample, consisting of Sheep Mountain porphyry, was collected in order to define the crystallization age of this unit and test its possible association with the gold-bearing Cretaceous Howell Creek suite.

Heavy mineral concentrates were prepared by standard techniques (crushing, grinding, Wilfley™ table, heavy liquids), and sorted by magnetic susceptibility using a Frantz™ isodynamic separator. SHRIMP analytical procedures followed those described by Stern (1997), with standards and U-Pb calibration methods following Stern and Amelin (2003). Briefly, zircons were cast in 2.5 cm diameter epoxy mounts along with fragments of the GSC laboratory standard zircon (z6266, with $^{206}Pb/^{238}U$ age = 559 Ma). The mid-sections of the zircons were exposed using 9, 6, and 1 µm diamond compound, and the internal features of the zircons (such as zoning, structures, alteration, etc.) were characterized in back-scattered electron mode (BSE) utilizing a Zeiss Evo 50 scanning electron microscrope. Mount surfaces were evaporatively coated with 10 nm of high purity Au. Analyses were conducted using an $^{16}O^-$ primary beam, projected onto the zircons at 10 kV. The sputtered area used for analysis was ca. 25 µm in diameter with a beam current of ca. 8 nA. The count rates at ten masses including background were sequentially measured over 5 scans with a single electron multiplier and a pulse counting system with deadtime of 25 ns. Off-line data processing was accomplished using customized in-house software. The 1σ external errors of $^{206}Pb/^{238}U$ ratios reported in Appendix 1 incorporate a ±1.1 % error in calibrating the standard zircon (see Stern and Amelin, 2003). No fractionation correction was applied to the Pb-isotope data; common Pb correction utilized the Pb composition of the surface blank (Stern, 1997). Isoplot v. 3.00 (Ludwig, 2003) was used to generate concordia plots and calculate weighted means. The error ellipses on the concordia diagrams, and the weighted mean errors are reported at 2σ. Analyses of a secondary zircon standard (Temora 2) were interspersed between the sample analyses to verify the accuracy of the U-Pb calibration. Using the calibration defined by the z6266 standard, the weighted mean $^{206}Pb/^{238}U$ age of seven SHRIMP analyses of Temora 2 zircon is 414 ± 6 Ma (95% conf.). The accepted $^{206}Pb/^{238}U$ age of Temora 2 is 416.5 +/-0.22 Ma (Black et al., 2004).

07RH-117: Nicol Creek intraflow sediment

The majority of zircon grains in this sample are rounded, consistent with a detrital origin (Fig. 7A). The zircons range from colorless to pale brown and are moderately to well rounded, with strong evidence of mechanical abrasion on the surface. Backscatter electron images (BSE) reveal broad, weak oscillatory zoning typical of grains of igneous origin. A total of 74 grains were analysed and $^{207}Pb/^{206}Pb$ ages range from ~1.43 to 3.5 Ga (Appendix 1, Fig. 8). There is no apparent correlation between grain morphology and age. The youngest concordant grain has a $^{207}Pb/^{206}Pb$ age of 1439 ±18 Ma. This grain constrains the maximum age of the Nicol Creek interflow sediment. In addition, the age of this grain is within error of a regionally restricted rhyolite to quartz latite flow (1443 ±7 Ma) from the Purcell lavas in Montana (Evans et al., 2000). Volcanic material was either directly contributed to the sediment, or earlier Nicol Creek volcanics were eroded to produce the interflow sediment. The 1439 ± 2 Ma age of a gabbro sill that cuts the Kitchener Formation (Brown and Woodfill, 1998) indicates that it is a feeder to the Nicol Creek volcanics.

07RH-70 – Sheep Mountain K-feldspar Porphyry

Zircons from this sample are colorless, euhedral and have sharply facetted crystals (Fig. 7B). Backscatter Electron images indicate two main components to the crystals. Concentric oscillatory growth zoning is apparent in most of zircon, but diffuse cores are also present in some grains. Ion probe analyses on 28 grains, including both cores and rims, yielded a series of discordant points that form a mixing line on the Concordia diagram (Fig. 9). A detailed examination of the BSE images indicates that the diffuse cores of many grains typically give much older ages than the oscillatory overgrowths or the cores of grains that do not have diffuse cores (Fig. 10). The 102 ±24 Ma lower intercept of this line is constrained by 12 concordant, or near concordant analyses. A weighted average age for these youngest grains (n=12) is 105.0±2.5 Ma. Barnes (2002) describes a series of small hypabyssal and intrusive bodies in southeastern B.C. termed the Howell Creek suite. These intrusions contain alkali feldspar and clinopyroxene phenocrysts (Bowerman et al., 2006) and yielded a ~102 Ma Ar-Ar age (Barnes, 2002). The similarity of petrology and age indicates that the Sheep Mountain porphyry is related to the Howell Creek suite.

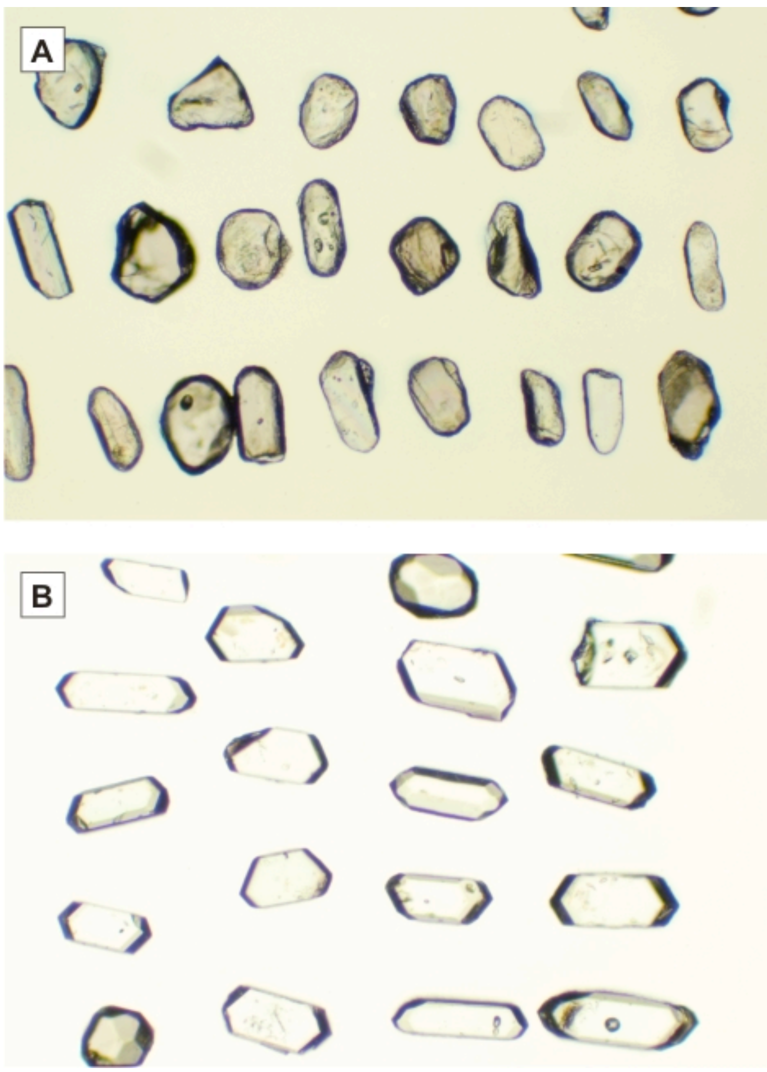

Figure 7. Plane light images of zircon from sample 07RH-117: Nicol Creek intraflow sediment (A) and sample 07RH-70 – Sheep Mountain K-feldspar Porphyry (B). Grains are 150 to 200 microns in length. The detrital origin of zircon from the Nicol Creek sediment is clearly indicated by the well abraded nature of the grains (A), as compared to the igneous nature of zircon from the Sheep Mountain porphyry (B).

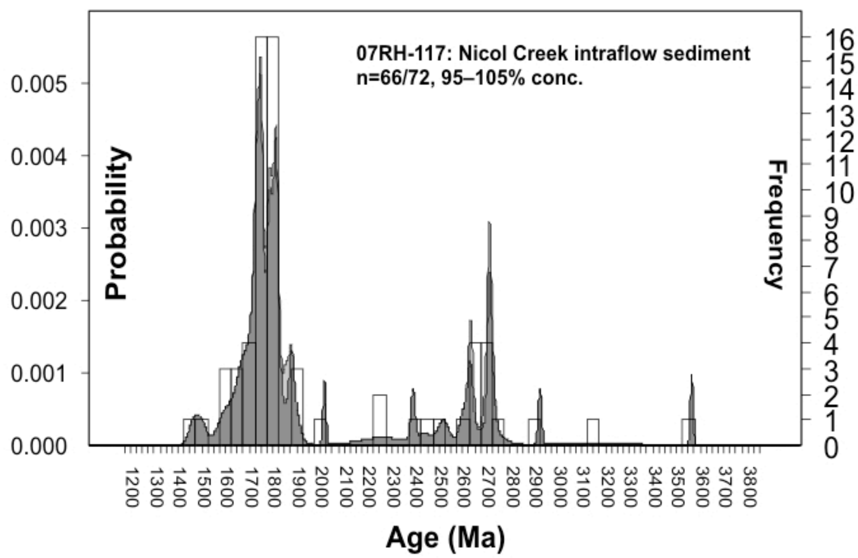

Figure 8. Frequency-Probability plot for detrital zircon from the Nicol Creek intraflow sediment (07RH-117). Only those zircon analyses that were between 95 and 105% concordant were used in this plot.

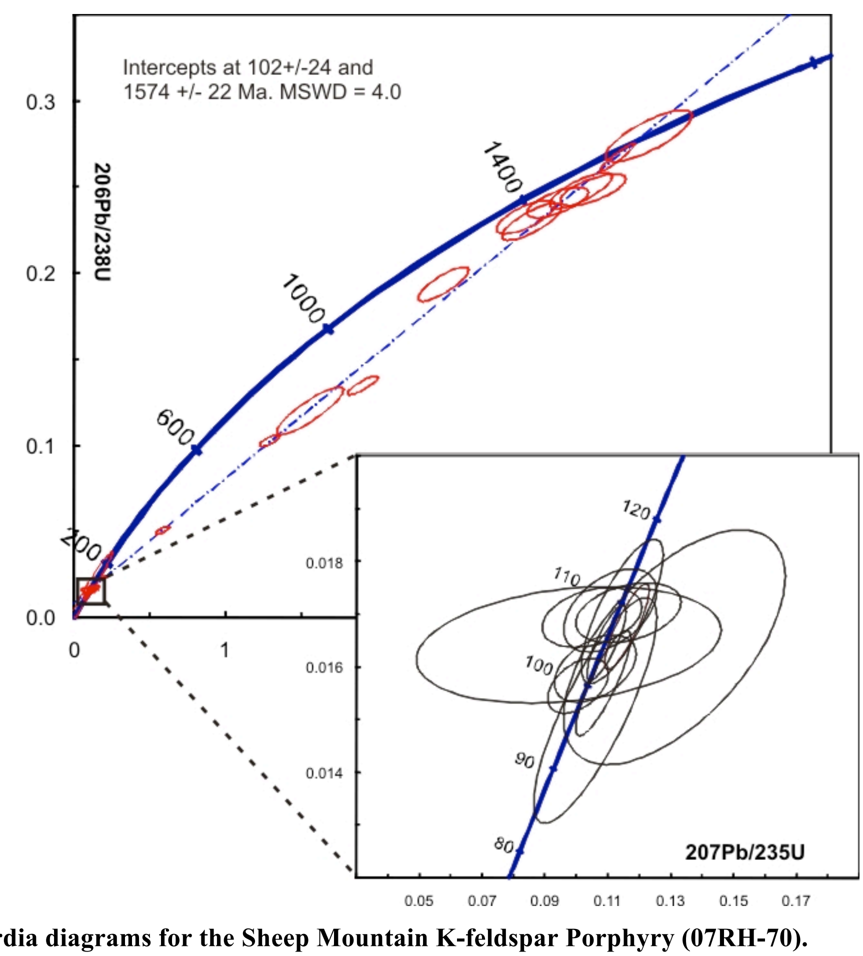

Figure 9. Concordia diagrams for the Sheep Mountain K-feldspar Porphyry (07RH-70).

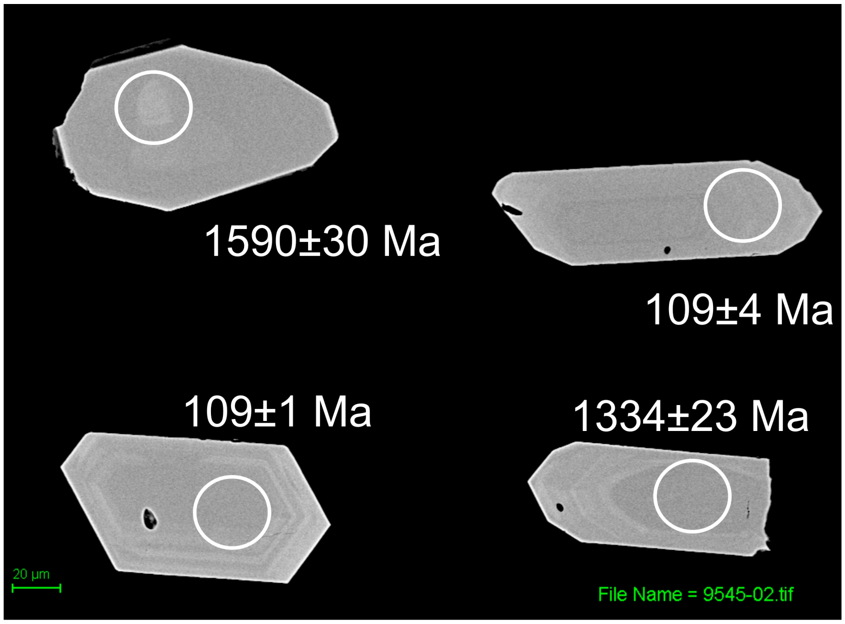

Figure 10. Backscatter electron images of zircons from 07RH-70 – Sheep Mountain K-feldspar Porphyry.

BIOGEOCHEMISTRY

An extremely thick blanket of overburden covers much of the Purcell Mountains near Cranbrook (e.g. Fig. 6e). This glacial overburden has placed a severe limitation on mapping and prospecting activities in the region. Outcrops are limited to steep cliff faces, roadcuts, and local ridges. Although this paucity of outcrop may have limited the success of prospecting and soil sampling, other methods can now be applied to the region in order to 'see through' this cover. Fortunately, forestry roads provide excellent access to most parts of the region.

Outer bark scrapings from lodgepole pine (*Pinus contorta*) were collected from 50 stations in the Tepee Creek area during July 2008. Each sample was oven-dried for 24 hours at 80^{o}C then milled to a fine powder in preparation for chemical analysis by Acme Laboratories in Vancouver. In addition to the 50 samples, 3 preparation duplicates and 3 samples of known composition (blind controls) were inserted. The samples were digested in nitric acid then aqua regia prior to analysis for 53 elements by ICP-MS (Acme's method 1VE-MS). Acme also included analytical repeats of two samples, 2 blanks, 2 flour samples with low element concentrations, and 4 internal control samples.

Data for selected elements are divided into 5 classes, each representing approximately 20% of the sample population. Selected element distribution patterns of all samples have been plotted (Fig. 11) by kriging the data and imposing the percentile break points (shown as color changes) listed in Appendix 2 using the software program "Surfer" (Golden Software Ltd.). Five samples that were collected outside the map area were not included in this analysis. In each case the 90th percentile has been taken as the 'maximum' and all values greater than the 90th percentile are plotted as the same color so that any outlier values do not overwhelm the geochemical variability in the dataset. The drainage pattern has been superimposed upon each plot, and where the kriging has extrapolated patterns in the west and northwest into areas with no sample control, the patterns have been masked.

Elements are grouped according to some similarities in distribution patterns. In particular, there appears to be a strong correlation between surface copper occurrences and increased abundances of Cu, Co, and Sb (Fig. 11). Other elements such as Pb, Ag, and Ni mimic the distribution of these elements. The surface zone of alteration has a background level of these elements, but is enriched in Mn, Ba and Cd. The Mn enrichment in the lodgepole pine bark fits well with the observed Mn oxide alteration in the area. From this small survey, it would appear that this biogeochemical technique has promise in exploration programs for sediment-hosted deposits in this environment.

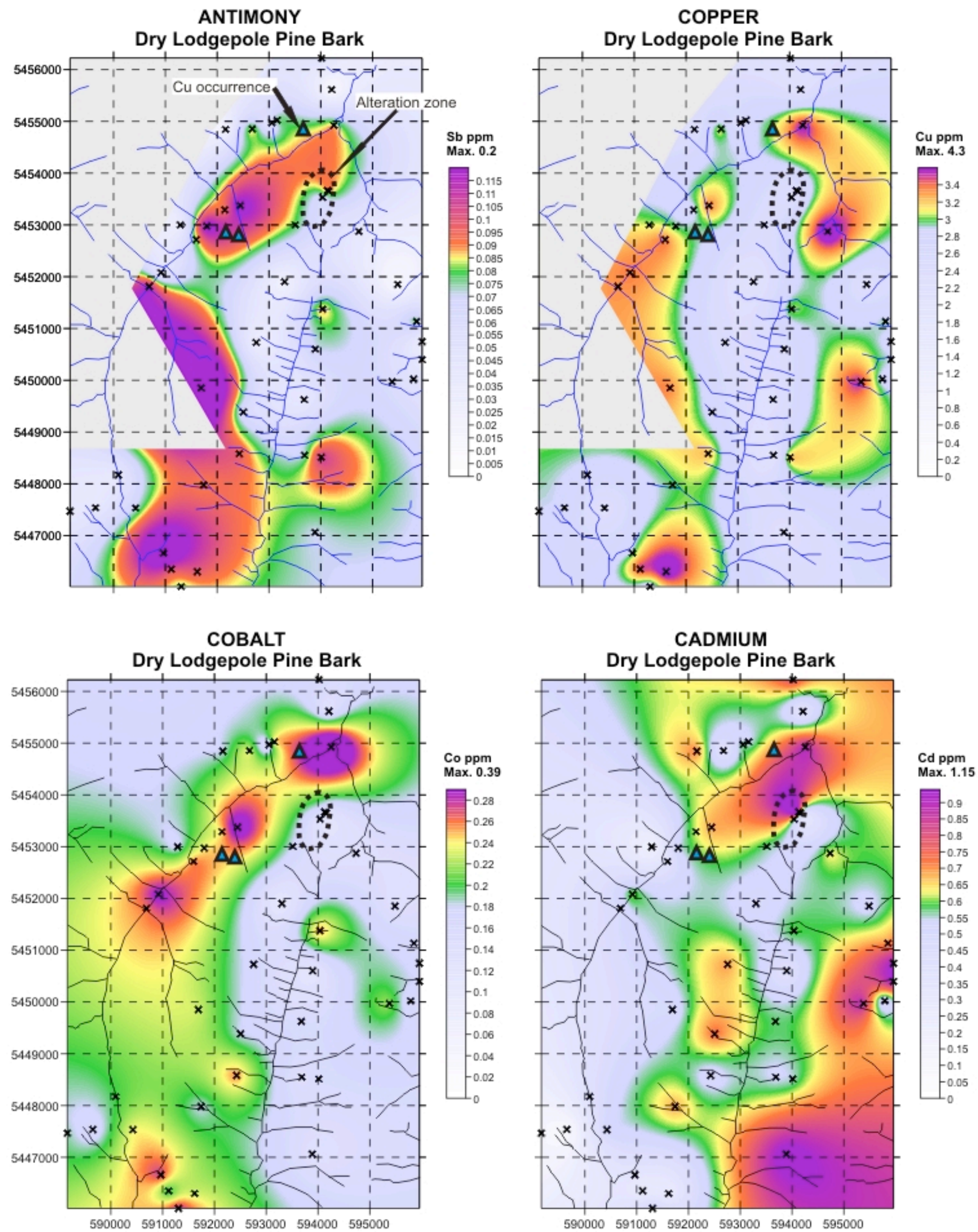

Figure 11. Element distribution maps for antimony, copper, cobalt and cadmium in lodgepole pine bark. All samples have been plotted by kriging the data (Appendix 2) with the 90th percentile taken as the maximum. The location of surface Cu-Ag occurrences and alteration are plotted for comparison.

DISCUSSION

The only currently recognized sediment-hosted stratabound Cu-Ag deposits in the Belt-Purcell basin occur within the Revett Formation of western Montana (Hayes and Einaudi, 1986; Boleneus et al., 2005). Roughly equivalent rocks of the middle Creston Formation also contain disseminated sediment-hosted Cu-Ag mineralization. Although minor sediment-hosted Cu mineralization has been noted in rocks of the Aldridge Formation (Höy, 1993), it appears that an important metallogenic change occurred at the onset of Creston Formation deposition. Lydon (2007) marks this transition as a change from rift-fill to rift-sag deposition. This transition is also thought to represent a change in the water column from one that is anoxic to one that contains dissolved oxygen. Evidence cited for the anoxic nature of the Aldridge Formation includes the turbiditic silty-argillite sedimentary succession with up to 3 wt. % organic carbon, and the occurrence of pyrrhotite as the dominant iron-sulfide (Goodfellow, 2000). In contrast, the appearance of sediment-hosted Cu occurrences within the Creston strata appears to be linked to the locally oxidized nature of these sediments. Red-bed style alteration identified in the Tepee Creek area likely represents movement of oxygen-enriched fluids through the stratigraphic column leading to diagenetic reddening of the middle Creston sandstones. These fluids were likely brines, owing to the shallow marine environment and the abundance of salt casts in the overlying Gateway Formation. These oxygenated brines, circulating in coarse sediments, may have reached their optimum ability to leach and carry trace metals like copper (Brown, 2005). Although relatively minor, the Tepee Creek Cu occurrences may represent the approximate location of a redox boundary. These occurrences lie stratigraphically below the Revett-equivalent middle Creston Formation and are hosted within sulfide bearing fine-grained “grey bed” sedimentary rocks. Mechanisms for driving fluid movement include sediment compaction, locally anomalous heat flow, and meteoric recharge (Brown, 2005).

The presence of a gabbro dike in close association with the Tepee Creek alteration zone and Cu occurrences may be indicative of a local link between mafic magmatism, increased heat flow and sediment-hosted Cu mineralization. This link is strengthened by the presence of Cu mineralization within mafic dikes in the Kitchener Formation and surrounding Nicol Creek volcanic rocks at the Roo occurrence. Stratabound Cu mineralization in the Revett Formation is considered to be epigenetic and diagenetic, with well defined alteration zones, but no defined link with increased heat-flow in the basin (Hayes and Einaudi, 1986). Therefore, the Tepee creek occurrences share many similarities with the Revett-hosted deposits, but the mechanism of fluid-metal transport may be somewhat different. Deposition of the Creston Formation is constrained between the 1468 Ma Moyie sills (Anderson and Davis, 1995) and the 1454 Ma middle Belt carbonate (Evans et al., 2000). Although the ca. 1439 Ma Nicol Creek Formation is slightly younger than the Creston Formation, emplacement of associated mafic dikes likely contributed to a higher regional heat flow, and a more rapid transport of basinal brines and associated metals.

Although sediment-hosted deposits (of Pb, Zn, Cu, Ag and Au) are clearly an important exploration target within the Belt-Purcell basin, the copper-polymetallic nature of Sheep Mountain demonstrates the local importance of porphyry-style mineralization. The Howell Creek intrusive suite is of the same age and is spatially associated with low-grade, disseminated gold mineralization (Barnes, 2002). Introduction or remobilization of metals by these intrusions may have created additional sediment-hosted, albeit porphyry-related deposits. Other Cretaceous intrusions in the region include the Reade Lake and Kiakho stocks (Höy, 1993). Highly permeable units, such as medium-grained sandstones in the Creston Formation, may aid in the development of post-sedimentation hydrothermal systems. However, reactive carbonate-bearing units, such as the Kitchener Formation, may have been more likely to have developed economic occurrences.

Although thick glacial overburden makes mapping and mineral exploration activities in the Cranbrook region especially difficult, biogeochemical element maps produced from results of lodgepole pine bark analysis appear to represent an effective exploration tool. Identification of overlapping anomalies between biogeochemical and traditional soil and stream geochemical surveys would likely prove more powerful.

ACKNOWLEDGEMENTS

Research funding for this project was provided by Geoscience B.C. and Targeted Geoscience Initiative 3 (TGI-3) of Natural Resources Canada. Bob Anderson, David Gardner, Dave Grieve, Craig Kennedy, Suzanne Paradis, David Pighin, and Timothy Hayes are thanked for their informative discussions on the geology and mineral resources of the Belt-Purcell Supergroup. Derek Feeback and Revett Minerals provided an excellent tour of the Troy Mine. Geophysical data and analysis was provided by Mike Thomas. Reviews by Alex Brown and Karl Evans contributed significantly to this article.

REFERENCES

Anderson, H.E. and Davis, D.W. (1995): U-Pb geochronology of the Moyie Sills, Purcell Supergroup, southeastern British Columbia: implications for the Mesoproterozoic geological history of the Purcell (Belt) Basin; Canadian Journal of Earth Sciences, v. 32, p. 1180-1193.

Barnes, E.M. (2002): The Howell Creek suite, southeastern British Columbia: mid Cretaceous alkali intrusions and related gold deposition in the Canadian Cordillera; M.Sc. Thesis, University of Alberta, Edmonton, Ab.

Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbell, I.H., Korsh, R.J., Williams, I.S., Foudoulis, C. (2004): Improved $^{206}Pb/^{238}U$ microprobe geochronology by monitoring of a trace-element-related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards; Chemical Geology, v. 205, p. 115-140.

Boleneus, D.E., Appelgate, L.M., Stewart, J.H. and Zientek, M.L. (2005): Stratabound copper-silver deposits of the Mesoproterozoic Revett Formation, Montana and Idaho; United States Geological Survey, Scientific Investigations Report 2005–5231, 66 p.

Bowerman, M., Christianson, A., Creaser, R.A. and Luth, R.W. (2006): A petrological and geochemical study of the volcanic rocks of the Crowsnest Formation, southwestern Alberta, and of the Howell Creek suite, British Columbia; Canadian Journal of Earth Sciences, v. 43(11), p. 1621–1637.

Brown, A.C. (1992): Sediment-hosted stratiform copper deposits; Geoscience Canada, v. 19, p. 125–141.

Brown, A.C. (2005): Refinements for footwall red-bed diagenesis in the sediment-hosted stratiform copper deposits model; Economic Geology and the Bulletin of the Society of Economic Geologists, 100(4), p. 765-771

Brown, D.A. and Woodfill, R.D. (1998): The Moyie Industrial Partnership Project: Geology and Mineralization of the Yahk-Moyie Lake Area, Southeastern British Columbia (82F/01E, 82G/04W, 82F/08E, 82G/05W); in Geological Fieldwork, 1997, British Columbia Ministry of Energy Mines and Petroleum Resources, paper 1998-1, p. 1-22.

Cailteux, J.L.H., Kampunzu, A.B., Lerouge, C., Kaputo, A.K., Milesi, J.P. (2005): Genesis of sediment-hosted stratiform copper-cobalt deposits, central African Copperbelt; Journal of African Earth Sciences, v. 42, p. 134-158.

Canet, C., Prol-Ledesma, R.M., Torres-Alvarado, I., Gilg, H.A., Villanueva, R.E., and Cruz, R. (2005): Silica-carbonate stromatolites related to coastal hydrothermal venting in Bahia Concepcion, Baja California Sur, Mexico; Sedimentary Geology, v. 174, pages 97-113

Cook, F.A. and van der Velden, A.J. (1995): Three-dimensional crustal structure of the Purcell anticlinorium in the Cordillera of southwestern Canada; Geological Society of America Bulletin, v. 107, p. 642-664.

Cox, D.P., Lindsey, D.A., Singer, D.A. and Diggles, M.F. (Revised 2007): Sediment-hosted copper deposits of the world: deposit models and database; United States Geological Survey, Open-File Report 03-107.

Evans, K.V., Aleinikoff, J.N., Obradovich, J.D. and Fanning, C.M. (2000): SHRIMP U-Pb geochronology of volcanic rocks, Belt Supergroup, western Montana: evidence for rapid deposition of sedimentary strata; Canadian Journal of Earth Sciences, v. 37, p. 1287–1300.

Gardner, D.W. and Johnston, S.T. (2007): Sedimentology, correlation, and depositional environment of the upper Purcell Supergroup, northern Purcell Basin, southeastern British Columbia; Geological Survey of Canada, Current Research 2007-A6, 13 p.

Garlick, W.G. (1988): Algal mats, load structures, and synsedimentary sulfides in Revett Quartzite of Montana and Idaho; Economic geology, v.83, p. 1259-1278.

Goodfellow, W.D. (2000): Anoxic Conditions in the Aldridge Basin during formation of the Sullivan Zn-Pb Deposit: Implications for the Genesis of Massive Sulphides and Distal Hydrothermal Sediments; Chapter in Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M., eds., The Geological Environment of the Sullivan Pb-Zn-Ag Deposit, British Columbia, Mineral Deposits Division of the Geological Association of Canada, Special Publication 1, p. 218-250.

Hartlaub, R.P. (2009): Sediment-hosted stratabound copper-silver-cobalt potential of the Creston Formation, Purcell Supergroup, south-eastern British Columbia (parts of NTS 082G/03, /04, /05, /06, /12); *in* Geoscience BC Summary of Activities 2008, Geoscience BC, Report 2009-1, p. 123–132.

Hartlaub, R.P. and Paradis, S. (2008): An Evaluation of the Geology and Stratabound Base Metal Potential of the Middle and Upper Purcell Supergroup (NTS 082G/03, 04, 05, and 06), Southeast British Columbia; in Geological Fieldwork 2007, British Columbia Ministry of Energy Mines and Petroleum Resources. Paper 2008-1, p. 9-16.

Hayes, T.S. and Einaudi, M.T. (1986): Genesis of the Spar Lake strata-bound copper-silver deposit, Montana: Part I, controls inherited from sedimentation and pre-ore diagenesis; Economic Geology, v. 81, p. 1899–1931.

Hitzman, M.W. (2000): Source basin for sediment-hosted stratiform Cu deposits: implications for the structure of the Zambian Copperbelt; Journal of African Earth Sciences, v. 30, p. 855-863.

Höy, T. (1985): The Purcell Supergroup Fernie west-half Southeastern British Columbia, Part A - Stratigraphy -Measured Sections; British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 76, 79 p.

Höy, T. (1993): Geology of the Purcell Supergroup in the Fernie west-half map area, southeastern British Columbia; British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 84, 157 p.

Höy, T. and Carter, G. (1988): Geology of the Fernie west half map sheet (and part of Nelson east half) (082G/W half, 082F/E half); British Columbia Ministry of Energy, Mines, and Petroleum Resources, Open File 1988-14, scale 1:100 000.

Höy, T., Price, R.A, Legun, A., Grant, B., and Brown, D. (1995): Purcell Supergroup, Geological Compilation Map; British Columbia Ministry of Energy, Mines and Petroleum Resources, Geoscience Map 1995-1, scale 1:250 000.

Ludwig, K.R. (2003): User's manual for Isoplot/Ex rev. 3.00: a Geochronological Toolkit for Microsoft Excel; Special Publication, 4, Berkeley Geochronology Center, Berkeley, 70 p.

Lydon, J.W. (2007): Geology and metallogeny of the Belt-Purcell Basin; *in* Mineral Deposits of Canada: A synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, Goodfellow, W.D., editor, Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p. 581–607.

Mauk,J.L. and Hieshima, G.B. (1992): Organic matter and copper mineralization at White Pine, Michigan, U.S.A.; Chemical Geology, v. 99, Issues 1-3, p. 189-211.

Mauk, J. L., Kelly, W. C., van der Pluijm, B. A. and Seasor, R. W. (1992): Relations between deformation and sediment-hosted copper mineralization: Evidence from the White Pine part of the Midcontinent rift system; Geology, v. 20, p. 427-430.

Mauk, J.L. and White, B.G. (2004): Stratigraphy of the Proterozoic Revett Formation and its control on Ag-Pb-Zn vein mineralization in the Coeur d'Alene district, Idaho; Economic Geology, v. 99, p. 295–312.

McGimsey, R.G. (1985): The Purcell lava, Glacial National Park, Montana; United States Geological Survey, Open File Report 85-0543, 191 p.

McMechan, M.E. (1981): The Middle Proterozoic Purcell Super-group in the Southwestern Purcell Mountains, British Columbia and the Initiation of the Cordilleran Miogeocline, Southern Canada and Adjacent United States; Bulletin of Canadian Petroleum Geology, v. 29, p. 583-621.

McMechan, M. E., Höy, and Price, R.A. (1980): Van Creek and Nicol Creek formations (new); a revision of the stratigraphic nomenclature of the middle Proterozoic Purcell Supergroup, southeastern British Columbia; Bulletin of Canadian Petroleum Geology, v. 28, p. 542-558.

Nash, J.T. and Hahn, G.A. (1989): Stratabound Co-Cu deposits and mafic volcaniclastic rocks in the Blackbird mining district, Lemhi County, Idaho; *in* Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V., eds., Sediment-hosted stratiform copper deposits: Geological Association of Canada, Special Paper 36, p. 339-356.

O'Brien, D.C. (1968): Cubic casts as indicators of 'top and bottom' in the Shields Formation (Precambrian Belt Supergroup); Journal of Sedimentary Petrology, v. 38, pages 685–687.

Price, R.A. and Sears, J.W. (2000): A preliminary palinspastic map of the Mesoproterozoic Belt-Purcell Supergroup, Canada and USA: implications for the tectonic setting and structural evolution of the Purcell anticlinorium and the Sullivan deposit; *in* The Geological Environment of the Sullivan Deposit, British Columbia, Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E. (eds.), Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 61–81.

Schofield, S. J. (1915): Geology of the Cranbrook Map Area, B.C.; Geological Survey of Canada, Memoir 76, 245 p.

Slack, J.F. (2006): High REE and Y concentrations in Co-Cu-Au ores of the Blackbird District, Idaho; Economic Geology, v. 101, p. 275-280.

Stern, R.A. (1997): The GSC Sensitive High Resolution Ion Microprobe (SHRIMP): analytical techniques of zircon U-Th-Pb age determinations and performance evaluation; *in* Radiogenic Age and Isotopic Studies, Report 10, Geological Survey of Canada, Current Research 1997-F, p. 1-31.

Stern R. (1999): In situ zircon trace element analysis by high mass-resolution SIMS; Ninth Annual V.M. Goldschmidt Conference, p. 284-285.

Stern, R.A., and Amelin, Y. (2003): Assessment of errors in SIMS zircon U-Pb geochronology using a natural zircon standard and NIST SRM 610 glass; Chemical Geology, v. 197, p. 111-146.

Thomson, G.R. (1990): Diamond drilling report on the Roo 1–3 claims; BC Ministry of Energy, Mines and Petroleum Resources, Assessment Report 20700, 71 p.

Walker, R. (2005): Assessment Report for the Proximal Claims Fort Steele Mining Division, latitude 49°34' 37" N, longitude 115°42' 52" W.; B.C. ARIS #27955, 69p.

Winston, D. (1986): Stratigraphic Correlation and Nomenclature of the Middle Proterozoic Belt Supergroup, Montana, Idaho, and Washington; *in* Belt Supergroup: A Guide to Proterozoic Rocks of Western Montana and Adjacent Areas; Montana Bureau of Mines and Geology, Special Publication 94.

Winston, D., and Link, P.K. (1993): Middle Proterozoic rocks of Montana, Idaho and Eastern Washington: The Belt Supergroup; *in* Reed, Jr, J.C., Bickford, M.E, Houston, R.S, Link, P.K., Rankin, R.W., Sims, P. K., and VanSchmus W.R. (eds.), Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 487-517.

Yeager, D.A. and Ikona C.K. (1982): Geological and geochemical report on the Silver Pipe 1–16 mineral claims; BC Ministry of Energy, Mines and Petroleum Resources, AR10907.