CORDILLERAN SECTION

GAC

GEOLOGICAL ASSOCIATION OF CANADA

TGI-3 Workshop: Public Geoscience in Support of Base Metal Exploration

Programme and Abstracts

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Simon Fraser University
Vancouver, B.C.

TGI3 Program IGC3 Programme

British Columbia Geological Survey — Geological Survey of Canada / Commission géologique du Canada — Geoscience BC

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Method Development for Green-fields to Deposit-scale 3D Geologic Modelling illustrated with Case Studies from the Abitibi, Flin Flon and Bathurst TGI-3 Project Areas

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One of the objectives of the Geological Survey of Canada's third Targeted Geoscience Initiative Program (TGI3) was to update the geoscience knowledge base in VMS exploration camps across Canada through 3D geologic modelling. As a result, 3D *green-fields* to deposit scale models have been constructed for a number of TGI3 project areas that enhance subsurface insight and contribute to VMS-targeting. In addition, R&D initiatives were undertaken to address fundamental problems and limitations of applying the existing 3D modelling methods to VMS settings. This presentation gives an overview of methods under development and illustrates their applicability for *green-fields* to deposit-scale VMS settings in the Bathurst, Flin Flon and Abitibi TGI3 project areas.

Traditionally, 3D structural modelling in *green-fields* (areas with sparse or no drill holes) relies on labour-intensive compilation of multiple cross-sections from geological map data. The resulting 3D models are highly subjective, irreproducible and difficult to update when new subsurface information from drilling or geophysical surveys become available. We are developing reproducible vector field interpolation methods that constrain the regional 3D subsurface structure of *green-fields* domains using the 3 directional cosines of outcrop structural elements (bedding/foliation). Multiple solutions of 3D lithostratigraphic horizons and structures can be instantly generated by user-defined parameters that weigh local versus global structural geometry and styles. This work can be expanded to include additional geological parameters describing thickness variations of strata as well as constraints from topological relationships with other lithostratigraphic surfaces and structures.

The hole-to-hole correlation of lithostratigraphic markers in tectonically replicated VMS-hosting volcanic and volcaniclastic successions with rare diagnostic lithostratigraphic horizons or horizons of limited lateral extent is highly underconstrained. To address this problem, we are developing algorithms that match user-defined lithostratigraphic patterns with drill hole lithology logs to support hole-to-hole correlation and identify diagnostic transitions in lithofacies. Syn-volcanic intrusions can be bypassed by defining gaps in the lithostratigraphic search pattern while abrupt lateral lithofacies changes can be taken into account by sequencing multiple search patterns. If numerical multivariate attributes, such as geochemistry or geophysical log data are available, the 1D along drill path pattern matching can be combined with statistical pattern recognition in a contextual lithologic log classifier.

Traditional lithofacies models of ore-hosting horizons have been based on correlating interpreted lithologic contacts from adjacent mine sections or plans. Geostatistical lithofacies modeling offers an alternative that casts the problem in a probabilistic framework, yields reproducible multiple scenarios and assesses uncertainty. As opposed to 3D surface models, the resulting 3D grid models provide direct input to 3D forward modelling and inversion routines facilitating the reconciliation of geophysical and geological data.

Legacy data of giant VMS deposits are often the most spatially extensive and voluminous subsurface datasets available in mineral exploration camps and record relatively large continuous tracts of observed underground geology. These analogue datasets are often poorly archived, registered to poorly-specified mine coordinate systems and captured in a format that renders them unsuitable for constraining 3D models. Since many of these legacy datasets have been acquired by mining enterprises that do not exist any longer, there is a significant risk of losing these knowledge assets for good. We have developed input routines that capture the geological interpretation from drill hole logs and mine workings across multiple mine levels. The polygons of the 2D mine interpretations in shape files are vertically projected to their appropriate depth levels using batch routines. Lithologic contacts and structures are systematically encoded to facilitate the 3D reconstruction process. The resulting 3D models provided insights in the geological setting of giant ore deposits that were not possible before.

The essence of a head-frame to *green-fields* 3D mapping strategy is to conduct simultaneous data reconciliation at all scales and from multiple sources. Although in its infancy we believe we increase the potential for mineral discovery when we focus on developing a workflow that supports full 3D multi-scale integration as opposed to higher risk single scale and single data source targeting. Future work will be undertaken to support upscaling methods, cross disciplinary data reconciliation and 3D interpretative environments with this theme in mind. This is Geological Survey of Canada Contribution 20090394.

Use of portable x-ray fluorescence spectrometry in vectoring for base metal sulfide exploration[#]

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Portable x-ray fluorescence spectrometers (PXRF) have been greatly improved over the last few decades such that they now can find far-reaching application in geology and geochemistry. Herein, we review features of available PXRF, discuss their benefits and limitations, and give practical suggestions and guidelines for their selection and use in mineral exploration. Finally, we present several case-studies from our recent work in the Abitibi Greenstone Belt, Quebec and Ontario and the Bathurst Mining Camp, northern New Brunswick.

In energy dispersive x-ray fluorescence spectrometry, a sample is bombarded by x-rays that cause the atoms within the sample to fluoresce (i.e., give off their own characteristic x-rays) and this fluorescence is then measured, identified and quantified. The energy of the characteristic x-rays identify the elements present in the sample and, in general, the intensities of the x-ray lines are proportional to the concentration of the elements in the sample, allowing quantitative chemical analysis.

Over the last few years, miniaturized x-ray tubes have largely replaced previously used radioisotope sources for most applications as these provide higher x-ray fluxes, shorter count times, and better precision. Silicon positive intrinsic negative (SiPIN) detectors are most commonly used today, and these convert incoming x-ray signals to voltage that is proportional to the energy of the incoming x-rays; these voltages are then sorted by a multichannel analyzer and fed to a miniature computer. Their energy resolution is too low to permit detection and quantification of many of the key light elements (LE; Mg, Al, Si). However, recent improvements that have placed the analytical path in a vacuum rather than air (most presently available PXRF) are offered as options on some models. Because low energy x-rays generated by LE are attenuated in air, its removal maximizes the x-rays that are detected. Within the last year, silicon drift detectors (SDD) have become an available option in many PXRF; they have a higher energy resolution and count rates, providing better precision and shorter analytical times, thus making them much more suitable for measurement of LE in an air path.

Hand-held PXRF are available in a lightweight pistol and bench-top forms. Bench-top PXRF are slightly larger and heavier, and have a more powerful tube than most hand-held PXRF, which provides better precisions and detection limits for many elements; both can be operated by battery power. Numerous accessories are available for PXRF, and several manufacturers have optimized their products for geological and geochemical applications, including Thermo Fisher Scientific and Innov-X Systems.

Geological and geochemical applications of PXRF generally require multi-element analysis; however, the more elements that are included within an analytical test, the greater the likelihood of problems such as peak overlaps or interferences, and manufacturers typically will provide machine calibrations for 20-30 elements in a particular analytical mode (see below). Our instruments have been calibrated for a range of elements for characterization of lithological units, different mineralization types and associated hydrothermal alteration, and other geochemical exploration vectors.

Fundamental Parameters (FP) are universal standardless, factory built-in calibration programs that describe the physics of the detector's response to pure elements, correction factors for overlapping peaks, and a number of other parameters to estimate element concentration while theoretically correcting for matrix discrepancies. FP should be used for accurately measuring samples of unknown chemical composition in which concentrations of light and heavy elements may vary from ppm to high percent levels. Compton Normalization (CN) is an "internal" standard, in which spectra are normalized to the Compton peak, which is produced by incoherent backscattering of the source radiation and is present for every sample. The intensity of the incoherent radiation backscatter reflects both the composition of LE in the sample matrix as well as the overall concentration of detectable elements. LE-dominant matrices produce a larger Compton peak, so this method provides the best results for measurement of sub-percent concentrations of heavy elements in samples composed mainly of LE.

Our instruments have 4 analytical modes, with the first two being most useful as they are relatively insensitive to sample matrix composition: 1) Process Analytical: employs FP and should be used for analysis of "ore grade or style" mineralization with some gangue; this provides "assay" level data and typical detection limits (DL) of 0.5 wt%. 2) "Soils": employs CN and should be used for analysis of soils, rocks, and other materials with a predominantly LE matrix; gives "geochem" level data at DL varying between 1 and 100 pm. 3) Empirical Analysis: uses reference standards to establish an empirical calibration line, and can be useful for samples where all major elements present cannot be analyzed. The standards should be matrix-matched and contain a range of element concentrations bracketing the desired level of quantification. 4) "Analytical" or "Alloys": employs FP and should be used for native metals and provides typical DL of 0.1-0.5%.

PXRFs are well-suited to myriad applications, spanning the entire exploration, mining, and remediation cycle. Among these are: 1) geological surface and underground mapping; 2) geochemical exploration (rock, soil and stream sediment surveys); 3) determination of metal contents of mineralized samples, mineral identification during prospecting and logging of drill core and cuttings; 4) mining and mineral processing grade control; and 5) environmental baseline and monitoring studies.

PXRF analyses were used to assist in distinguishing between different volcanic units of the Chibougamau area on the basis of high field strength elements (HFSE; Ti, Zr, Y), and to characterize the base metal contents of mineralization intersected in drillcore in the footwall of the Lemoine VMS deposit, Quebec (Fig. 1). Two major units can be recognized on the basis of HFSE contents: high Ti-low Zr, and high Zr-low Ti. PXRF Zr abundances are very similar to ICP-ES analyses of fewer selected samples, but an applied correction factor of 1.5 was necessary for PXRF Ti to match ICP values. However, data for both methods readily distinguished the units. The Cu-Zn-enriched nature of mineralization is correctly identified by both methods.

PXRF analyses of drillcores of sulfidic black shales intercalated with volcanic rocks of the Kidd-Munro Assemblage were used to differentiate between sedimentary horizons that contain a hydrothermal component and those that do not. The characterization of the element enrichment suite and metal abundance data of the former are being used to vector toward concealed hydrothermal vent sites and mineralization. Figure 2 depicts geochemical profiles for Cu and Zn in 3 drillcores situated stratigraphically along 2.3 km of strike length and located about 8 km north of the Kidd Creek Zn-Cu-Pb-Ag mine, Ontario, as determined by hand-held and bench-top PXRF. The figure shows that of the 3 broadly spaced argillite-bearing intervals, only the stratigraphically lowermost contains a hydrothermal signature whereas the upper 2 are barren. Within this horizon, diagnostic decoupled distribution of Cu and Zn is not evident in conventional assay data but is clearly recognized in PXRF analyses. Vectoring along this lower horizon may guide further exploration.

Powdered samples of banded iron formation exhalites that are spatially and temporally associated with VMS mineralization in the Ordovician Bathurst Mining Camp of northern New Brunswick were analyzed by PXRF. These data were then compared with previously obtained high-quality laboratory bulk compositional data in order to evaluate the efficacy of PXRF analyses in lieu of laboratory data and test applicability of PXRF in vectoring. There is generally good agreement between PXRF and laboratory data (except for high-Fe samples, as noted above; a few elements required application of correction factors). Elements of hydrothermal origin that can be analyzed by PXRF and which vary with distance from known VMS deposits include: Fe, Mn, Ca, Sr, Ba, Pb, Zn, Bi, Cu, Sb, and Sb. Proportional symbol maps for various elements and element ratios highlight anomalies similar to laboratory data (e.g., Fig. 3), and show that PXRF analyses serve as a primary vectoring tool that can replace time consuming, more costly laboratory analyses.

Preliminary testing of the use of PXRF in analysis of glacial till was conducted in the vicinity of the Halfmile Lake VMS deposit area, also located in the Bathurst Mining Camp. PXRF data were collected for dry, <63 µm (silt+clay) fraction till that were previously analyzed by high-quality laboratory methods. These laboratory data (Cu, Zn, Pb, Au, Sn, In, As, Sb, Hg) were previously used to define an eastward trending glacial dispersal train. Bulk, unprocessed (moist, coarse+fine) till was also analyzed by PXRF from 35 of the 55 original sample sites. In general, there is remarkably good agreement between PXRF data (e.g., Cu, Pb, Zn, As) for dry and moist tills, and the laboratory data. These results indicate that PXRF can be used to detect metal-rich till, either to guide sampling for laboratory analyses or direct detection of glacial dispersal trains in the field.

PXRFs provide rapid, in-situ, low cost, non-destructive, quantitative and/or qualitative multi-element analyses of many different sample media that require little or no sample preparation and instrument calibration for varied applications. The examples presented here illustrate the use of PXRF in mapping rock units and mineralized zones, and also vectoring toward mineralized sources using rocks and surficial material.

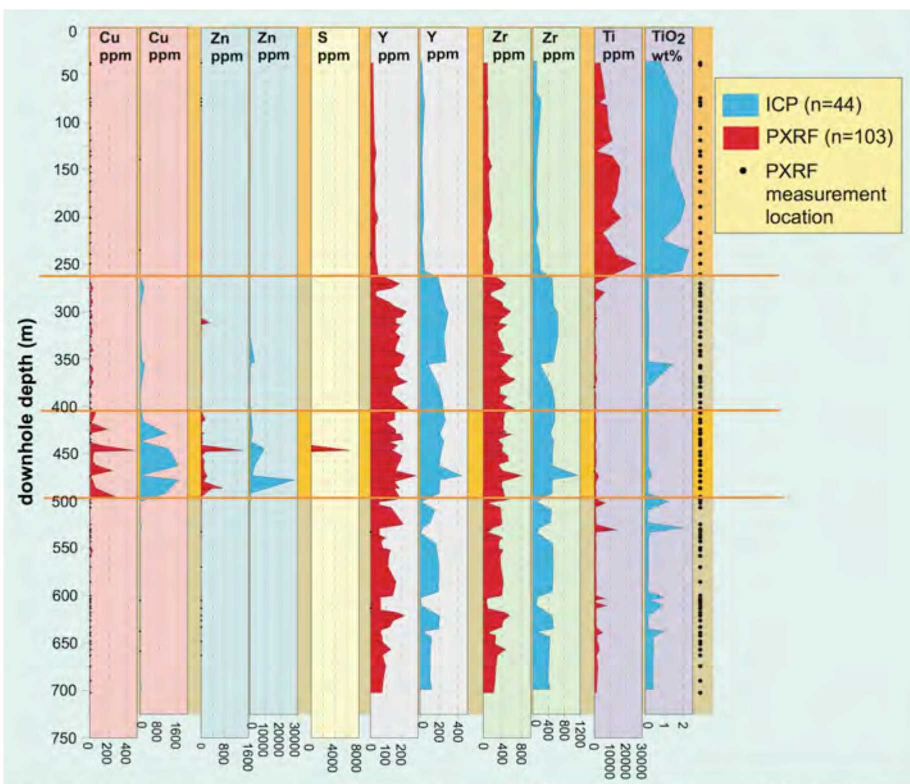

Fig. 1. Downhole log of selected element abundances in a part of drillcore LEM-40 from the footwall of the Lemoine VMS deposit, Chibougamau, Quebec as determined by conventional ICP and hand-held portable x-ray fluorescence spectrometer.

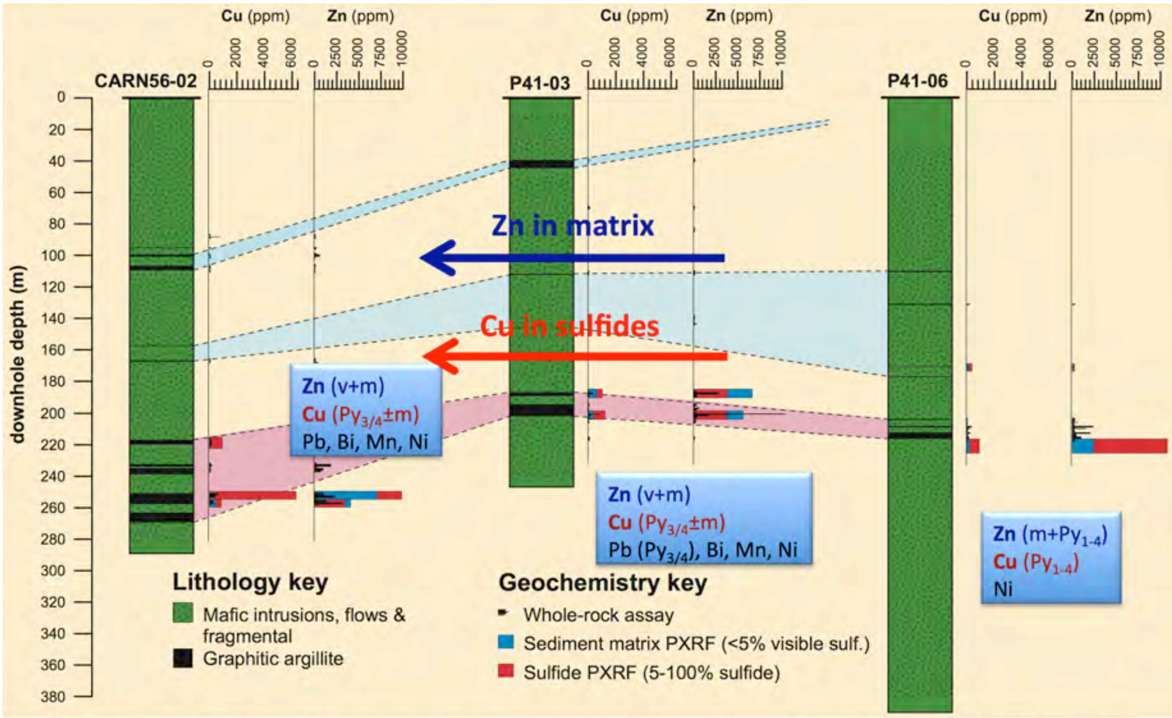

Fig. 2. Fence diagram of downhole Cu and Zn abundances in sulfide nodules, concretions, crusts and laminae and matrix of graphitic argillite intersections in three drillcores 2.5 km apart and 8 km north of the Kidd Creek mine, as determined by benchtop and hand-held PXRF.

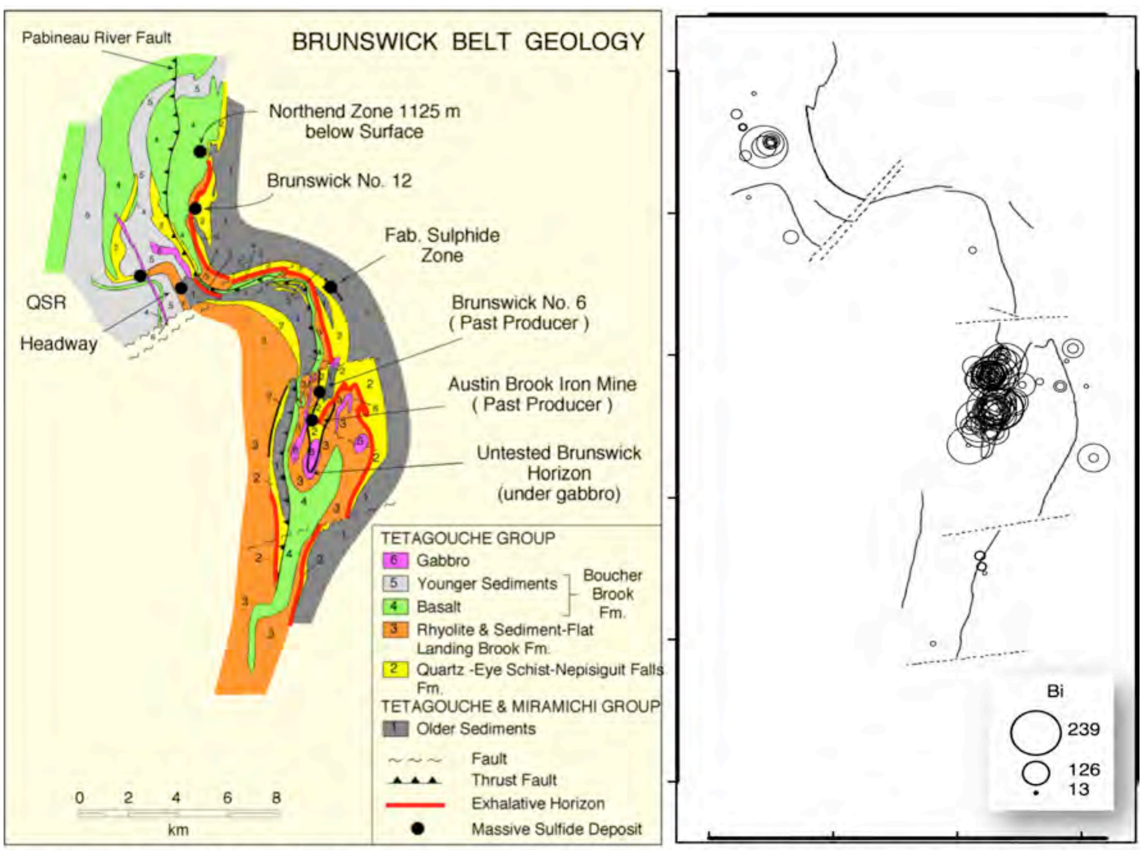

Fig. 3. Left: geology map of the Brunswick Belt. Right: proportional symbol map showing surface trace of iron formation horizon, and Bi content (ppm) of iron formation sample powders, as determined by benchtop portable x-ray fluorescence spectrometer.

Portable XRF and laser-ablation ICP-MS as vectoring tools in base metal exploration: Examples from the Kidd Creek Mine area

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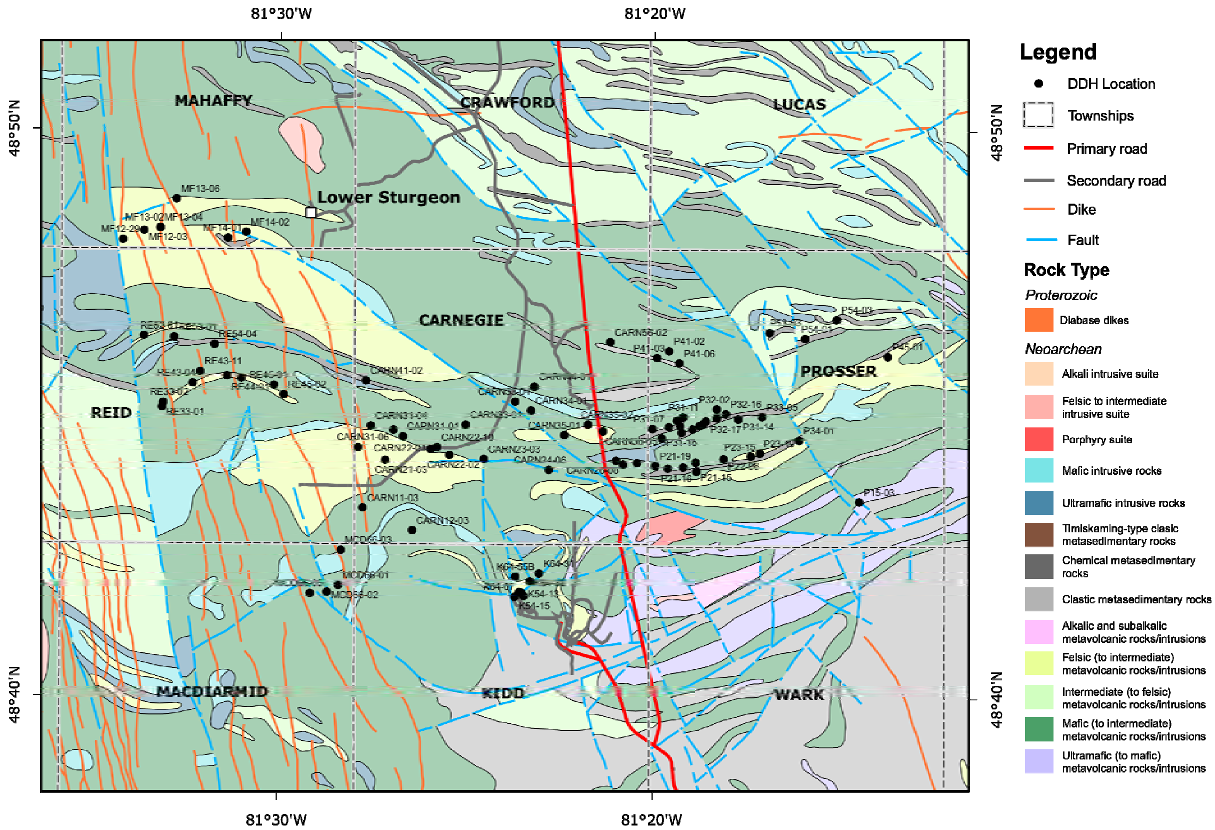
ABSTRACT
Sulfidic black shales are commonly present in ancient subaqueous volcanic sequences, where each horizon likely represents a significant hiatus in volcanic activity and deposition. These shales form geophysical anomalies (conductors) that are routinely drilled during exploration for volcanogenic massive sulfide (VMS) base metal deposits.

The objectives of our study are to provide an accurate, precise, robust and cost effective framework within which sedimentary horizons can be assessed to provide evidence of: a) the presence or absence of hydrothermal metal input; b) the type of hydrothermal activity recorded within, and prospectivity of, any one horizon; and c) the direction, along strike and down dip extent, and relative distance to the coeval venting centre (where a single horizon has been intersected more than once). This was achieved by the combination of geochemical analytical methods including: conventional whole-rock analysis, laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and portable x-ray fluorescence (pXRF) analysers; each optimized for different spatial resolution, and with varying cost and sensitivity characteristics.

GEOLOGY AND MINERALOGY
Metalliferous sedimentary rock horizons occur as intercalations within volcanic rocks of the 2.7 Ga Kidd-Munro assemblage (KMA) of the Abitibi sub-province, Canada (Fig. 1). The horizons are widely distributed within the KMA and commonly occur as carbonaceous (graphitic) and/or sulfidic argillaceous shale. Multiple intersections may be present in any one drillcore, representing both primary depositional stratigraphy and subsequent fold repetition.

Pyrite and pyrrhotite are the dominant sulfides in the shale horizons, with minor sphalerite, galena and chalcopyrite. Iron sulfides occur in six distinct textural habits: Py1, pyrite-rich laminae and framboids (sub-mm to 1 cm; primary chemical sedimentary); Py2, recrystallized and remobilized laminae and disseminations (early diagenetic); Py3, crustiform bands displaying growth textures and banding, commonly much disrupted (0.3 to 2 cm wide; early to late diagenetic); Py4, nodules displaying no internal fabric, and concretions displaying concentric zonation (0.5 to 4 cm diameter; early to late diagenetic); Py5, metamorphic porphyroblasts, over-growths and pressure shadows (0.2 to 3 cm diameter; peak to post-peak metamorphic). Finally, Py1 to Py4 have been subject to variable late-stage replacement by secondary pyrrhotite.



Modified from: Ayer, J.A., Trowell, N.F. and Josey, S. 2004. Geological compilation of the Abitibi greenstone belt; Ontario Geological Survey, Miscellaneous Release—Data 143.

Figure 1. Sampled diamond drill hole collar locations, within the western Kidd-Munro assemblage, N. Ontario.

Kilometers
0 1 2 3 4 5 6

WHOLE-ROCK GEOCHEMISTRY

The metal budget of any individual shale horizon reflects a variable admixture of materials with a number of end member compositions. Principal component analysis (PCA) of bulk sample geochemical data has been used to identify element associations that reflect major source contributions. Plotting first and second principal components of whole rock geochemical data has identified three dominant element groupings: 1) hydrothermal – Ag, As, Bi, Cd, Cu, Hg, In, Mo, Ni, Pb, Sn, Te, Zn; 2) hydrogenous – Au, Ca, Cr, Mn, Pt, Sb, Sc, Tl, V; and 3) terrigenous – Al, Ba, Be, Ce, Cs, Dy, Er, Eu, F, Ga, Gd, Hf, Ho, La, Lu, Mg, Nb, Nd, Pr, Rb, Sm, Sr, Ta, Tb, Th, Tm, U, Y, Yb, Zr. Iron and S do not have eigenvalues consistent with the major PCA groupings, and their eigenvalues in the second principal component suggest that their abundance may in fact be due to water column, rather than hydrothermal, processes. Hence, absolute pyrite and pyrrhotite abundance are poor indicators of hydrothermal input to black shales.

LASER-ABLATION ICP-MS

In-situ LA-ICP-MS trace element analysis of Fe-sulfides of various textural types was used to investigate inter-element correlations and sulfide end-member compositions. Trace elements showing significant enrichment in early pyrite include Ag, Au, As, Bi, Cu, Pb, Sb, Sn, Tl and Zn, whereas Co, Ni, Mo, Se, Pt and Te enrichments relatively enriched in later pyrite. Comparison of these element groupings with those determined from bulk chemical analyses highlights further the complex nature of element distributions and associations within the sulfide component of the KMA black shale horizons. Recrystallization, annealing and metamorphism tend to exclude trace elements from the pyrite structure (Fig. 2). In general, the early, visibly included pyrite forms (Py1 to Py3) have the greatest trace element contents, and later,

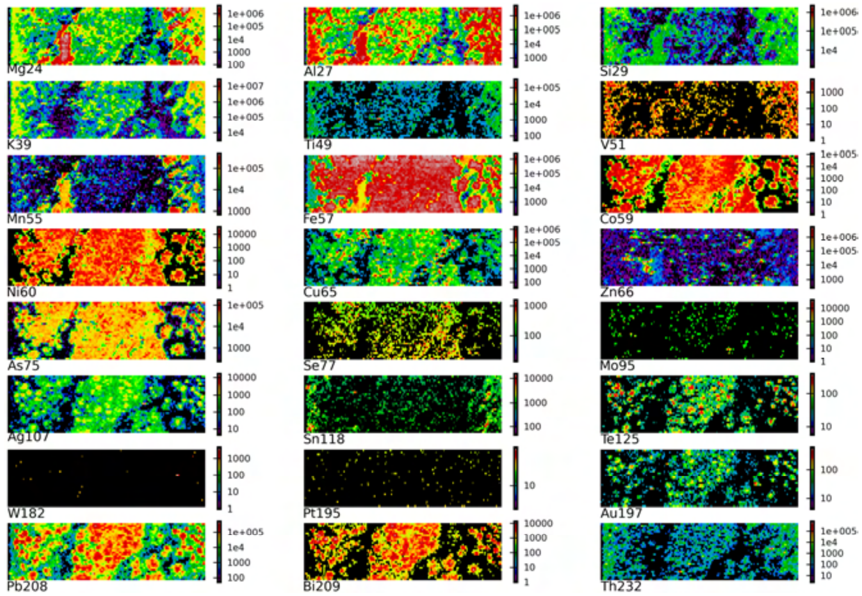


Figure 2. Laser-ablation ICP-MS maps for a selection of elements. The mapped portion of the sample is shown below (scale bar is 5 mm). Relict Py1 microcrystals are seen as bright spots (e.g. Ag, Pb, Au) within and partially recrystallized to Py2.

inclusion-free metamorphic pyrite (Py5 and pseudomorphic pyrrhotite) contains the lowest trace element abundances.

PORTABLE XRF

The analysis window of most pXRF instruments is approximately 1 cm in diameter, therefore these offer a compromise between the spatial resolution offered by micro-analytical techniques such as LA-ICP-MS, and the bulk sample integration of traditional chemical analysis methods. Some of the highest base metal and associated element contents we measured in the field (e.g. Zn ≈ 1.4 wt%; Cu ≈ 600 ppm; Mn ≈ 1 wt%; Cd ≈ 90 ppm; Hg ≈ 50 ppm) are in apparently (to the naked eye) sulfide-free shale. The majority of such enrichments appear to be due to the incorporation of disseminated, very fine-grained, Fe-rich sphalerite. In many instances this is not evident even when using a hand lens, and care must be taken not to overlook these cryptic enrichments. Pyrite commonly displays distinctly different trace element abundances than the host shale matrix. Figure 3 demonstrates that elemental abundances can vary significantly even between adjacent sulfide masses. Element exclusion is greatest where the associated pyrite is strongly recrystallized or is of metamorphic origin, with “dirty” concretions and crustiform material showing the least deviation from matrix abundances.

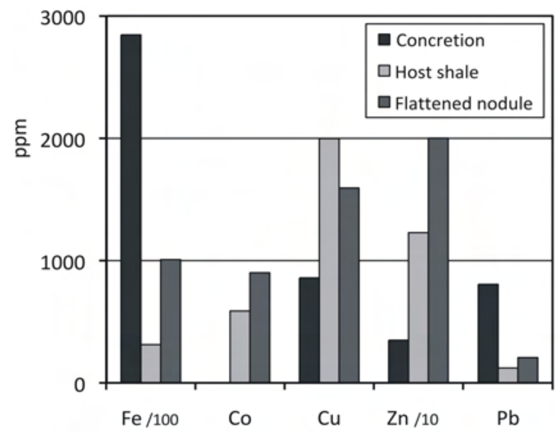
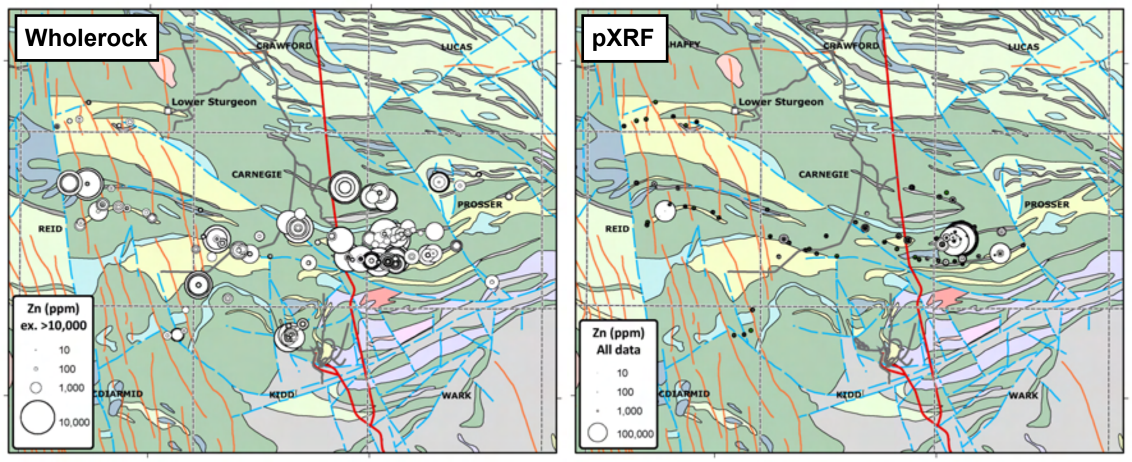


Figure 3. Selected portable XRF element analyses for two pyrite masses and their shale host. The two masses, both ~2 cm in diameter, are within 5 cm of one another.

VECTOR COMPARISON

By considering each method’s benefits and limitations it is apparent that each can be applied within an exploration program, but consideration must be made as to the type of information required. Hydrothermal geochemical signatures can be recognized by the use of traditional whole-rock geochemical analyses. However, these signatures are a result of elements hosted in multiple mineral phases and



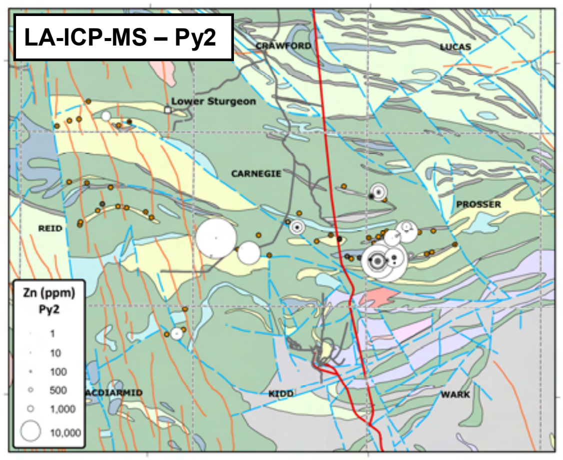


Figure 4. Comparison of Zn anomaly patterns as determined by wholerock, pXRF, and LA-ICP-MS geochemical analysis methods. (Key, see Fig. 1) The wholerock pattern is largely dependent on sampling density, reflecting widespread, abundant sphalerite veining developed throughout the exploration zone. PXRF analysis can avoid obvious veining, thus identifying anomalies hosted only in early sulfide and host matrix. LA-ICP-MS analysis of pyrite identifies Zn hosted in sphalerite microinclusions, suggestive of proximity to a vent site. As can clearly be seen, LA-ICP-MS provides a very powerful tool to highlight anomalies generated during formation of the sediment horizons, rather than secondary processes.

locations within a single horizon. In order to more effectively and efficiently rank areas meriting additional work in VMS exploration (Fig. 4) it is essential to understand the sources, distribution, and mineralogical and paragenetic association of geochemical signatures observed in shale horizons.

CONCLUSIONS

Various analytical methodologies have been assessed with respect to better constraining geochemical anomalies. Traditional whole-rock methods can integrate signals from a wide core interval, but are relatively expensive ($50+ per sample) and time-consuming. Laser-ablation ICP-MS analysis is a powerful tool for deconvolving sulfide chemistry and paragenesis, however, sample size is limited (making the technique prone to sampling bias), analysis costs are high, and lag times on data acquisition are long. Portable XRF analysis is non-destructive, provides cost-effective and essentially instantaneous information on sample composition, can be performed on site during a drill program, and can focus exploration targeting on the fly. A combination of the three approaches provides a comprehensive and powerful investigative methodology for elucidating element signatures in shale horizons, and opens the way for potential development of exploration vectoring protocols for application during routine core analysis.

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Development of surficial (soils and water) geochemical methods of exploring for base metal deposits at Howards Pass, Yukon.

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ABSTRACT

The Targeted Geoscience Initiative 3 (TGI3) Deep Search project includes research activities that aim to improve surficial geochemical vectors for buried base metal mineral deposits. These activities include investigations of the soils and waters around the XY deposit within Selwyn Resources' Howards Pass deposit, eastern Yukon, Canada. Two soil sampling transect lines were completed across the deposit, one in "easy" shallow colluvium, the other in "difficult" iron-cemented alluvium and colluvium. As expected, partial leach geochemical techniques detected the ore body in the easy case, but normalisation and statistical clustering were required to define a poor anomaly in the difficult case. In contrast to soil sampling, hydrogeochemical vectors to buried mineralisation are not yet well established as a mineral exploration tool. The Howards Pass surficial geochemical system includes substantial acid rock drainage (ARD). Examination of the biominerals and hydrogeochemistry of an ARD creek across the ore horizon demonstrates the hydrochemistry is essentially a product of biomineral-buffering, mineral neomorphism (aging), and groundwater-freshet seasonal hydrology. High Zn and Cu (up to 8.8%) in some biominerals suggests these may provide a vectoring method, but this initial data requires further follow-up. Seasonal water sampling strategies may perhaps deconvolute the groundwater geochemical signal from the surface plus groundwater signal.

INTRODUCTION

The Selwyn Basin in the Yukon Territory of Canada hosts major SEDEX Zn-Pb sulphide deposits, the biggest being the relatively large (~90.4 Mt) "XY" deposit at Howard's Pass (Fig. 1A), owned by Selwyn Resources (Goodfellow 2004). This research focuses on the surficial geochemical expression of the XY deposit. As part of the Deep Search Project within the GSC's Targetted Geoscience Initiative 3 Program (TGI-3), parallel soil sampling and acid rock drainage (ARD) investigations are being conducted at XY.

SOIL SAMPLING

Two soil sampling transects were completed in order to test partial leach protocols (Hall 1996) in different surficial cover types that in previous Selwyn Resources soil surveys reported contrasting results. Soil transect 1 was across an "easy" target, where the XY deposit is very shallowly buried <5 m by hillside colluvium. Soil transect 2 is a more "difficult" target where the orebody is buried by >5 m of alluvium and colluvium, some of which is heavily iron-cemented. The soil horizons analysed were the A horizon and the topmost and lowermost "B" horizons from each sample site. The partial leach protocols of Hall et al (1996) were used, and the analyses were conducted at GSC Ottawa's Inorganic Geochemistry Research Laboratory.

In "easy" soil transect 1 all partial leach protocols identified the orebody location within B horizon samples, with the lowermost "B" horizon samples producing the best anomaly (Fig. 1B). In the "difficult" soil transect 2 no partial leach protocol readily identified the orebody's location. However, for the lowermost "B" horizon soil samples, normalizing the iron-oxyhydroxide partial leach data against its major cations (Fe, Al, Ca) produced a weak coincident Pb-Zn anomaly (Fig. 1C). The better response of the lower B horizon medium is in contrast to the generally-preferred upper B horizon medium.

Petrographic and partial leach data suggest that this may be due to weathering of pyritic black shale detritus in the soil profile, a process that generates acidic pore waters. These would effectively remove Pb and Zn, which are subsequently fixed in carbonate-buffered areas (figure 2). Within the correlation matrix of the partial leach geochemistry, Zn mostly aligns with Ca, suggesting Zn mobility is probably controlled by carbonate-buffering of the pH to relatively high values, a common situation in surficial environments. Cluster analysis of the log-ratio-normalised geochemical data further suggests that soil samples primarily fall into Ca-rich and Ca-poor groups, a reflection of the acidic versus basic nature of the predominant local rock types (Rabbitkettle Formation carbonates and Road River Group sulphidic black shales). With such contrasting rock types, the detailed statistical analysis of these samples that is currently underway will likely yield further interesting observations.

HYDROGEOCHEMISTRY

An impressive ARD stream emanates from the hillside hosting the XY deposit (Fig. 1A, 2). Its hydrogeochemistry is buffered by various biologically-mediated mineral phases, primarily schwertmannite ($Fe^{3+}_{16}O_{16}(OH, SO_4)_{12-13}$ 10-12H_2O), ferrihydrite ($Fe_5O_3(OH)_9$), jarosite ($KFe^{3+}_3[(OH)_3/SO_4]_2$), and hydrobasaluminite ($AL_4[(OH)_{10}/(SO_4)_5]$ 12-36H_2O) (Fig. 2B). Some of these mineral phases (Fig. 2C) demonstrate significant preferential partitioning of base metals, with up to 8.8% Cu and 3% Zn. The high Cu and Zn values occur in biominerals from within sites with solid and water samples that overall have much lower Cu and Zn values, suggesting that this extreme partitioning is likely due to an as-yet undetermined biological process. However, a significantly larger dataset from more diverse sources is required in order to determine whether or not this partitioning property can be effectively used as a vector toward base metal mineralisation.

Seasonal sampling of individual sites demonstrates significant seasonal changes in ARD hydrogeochemistry, with values for some elements approaching an asymptotic value late in the season, implying that an accurate estimate of groundwater values can be derived from such studies. Such sampling may lead to a better utilisation of seeps and ARD as a vectoring tool. This sample suite further denotes changing saturation indices within single sites over the seasonal cycle. This would suggest that the calculation of saturation states seems to be a necessary step in the evaluation of ARD waters in order to ensure that trace element comparisons from water data are for samples on at least a roughly equivalent geochemical basis.

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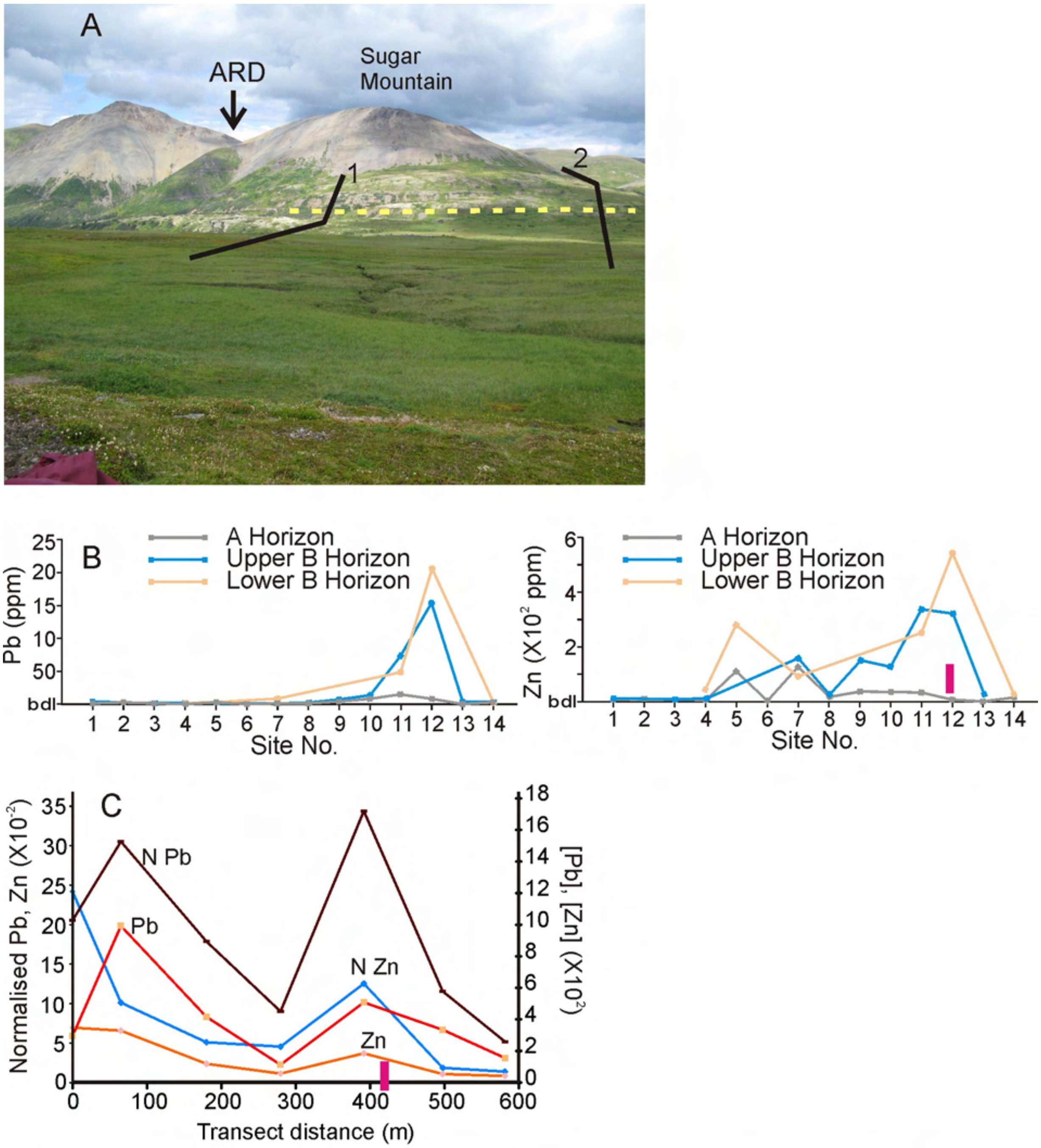

Figure 1. A - Physiography of the XY orebody looking north-northwest. An alluvial plain in the foreground gives way to outcrop and colluvium around the mountain. 1 and 2 denote the two soil sampling transects. ARD points to the gully on the western side of Sugar Mountain. that hosts the acid rock drainage. Yellow dashed line is the approximate surface projection of the XY orebody. B - Pb and Zn profiles in soil transect 1 for three different soil horizons. Site 1 is at the southern end of the transect, and sites are 100 m spaced. C - Pb, Zn, normalised Zn (N ZN) and normalised Pb (N Pb) profiles for soil transect 2.Note the two orders of magnitude greater Pb in this transect in comparison to the first. 0 m is at the southern end of the transect. For both B and C the XY orebody is located at the red bar.

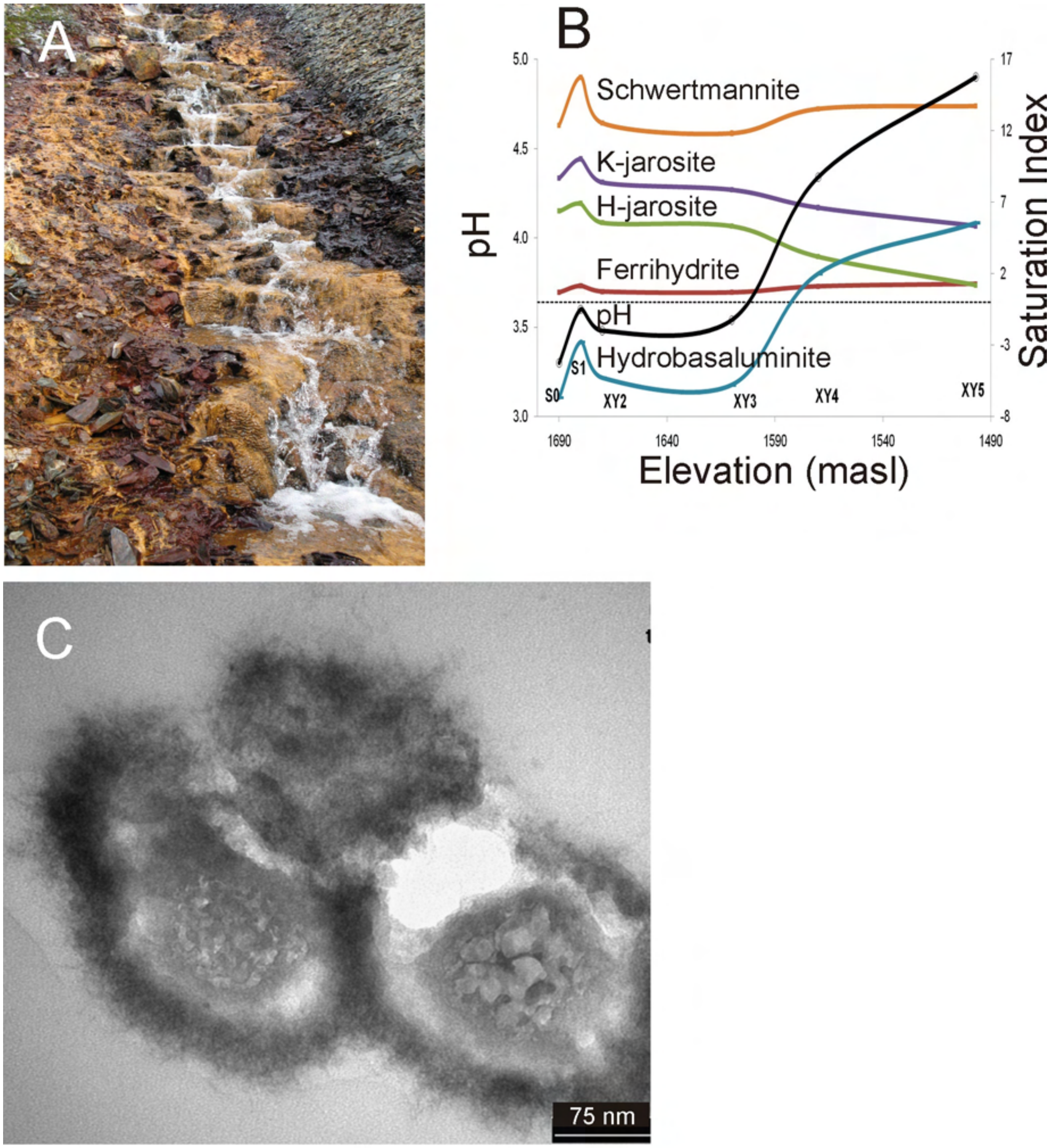

Figure 2. A - Iron oxyhydroxide biomineral terraces within the ARD stream emanating off the XY deposit. B - Saturation indices defined by Phreeq-c modelling for the ARD waters. Despite their oversaturation, different parts of the stream precipitate different minerals; e.g. the terraces in A are predominantly schwertmannite and ferrihydrite that age to goethite. The lower portions of the stream predominantly precipitate hydrobasaluminite despite high schwertmannite oversaturation. Sites are denoted by S and XY and elevation indicates downstream changes. The surface extrapolation of the orebody is between sites XY4 and XY5. C - TEM image of hydrobasaluminite biomineral precipitates around the cell. After cell death the internal portion of the cell becomes the site of mineral precipitation. EDS analysis indicate these biominerals have ~6% Cu and ~3% Zn.

Geochemistry and origin of geographically extensive Ni(Mo, Zn, U)-PGE sulphide deposits hosted in Devonian black shales, Yukon

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ABSTRACT

Nickel-PGE-rich sulphides hosted in Devonian black shales were first discovered in 1981 at the Nick property, Yukon. Subsequently, coeval occurrences were located by Cominco Limited (now Teck Resources) along the Monster River in the Ogilvie Mountains and a tributary of the Peel River in the Richardson Mountains (Fig. 1). In 1994, we discovered two additional occurrences along a small stream on the western margin of the Richardson Mountains (referred to as Eagle Plains) and along the south side of the Peel River (Fig. 1). These deposits were subsequently staked by Archer-Cathro & Associates and optioned to Quetzal Energy Ltd. Recent investigations of the Peel River area in 2008 led to the discovery of another deposit on the north side of the Peel River just east of the Peel River tributary occurrence. This deposit is unusual in that there is a lower and upper sulphide horizon although it is unknown whether they represent different stratigraphic levels or the same horizon repeated by faulting.

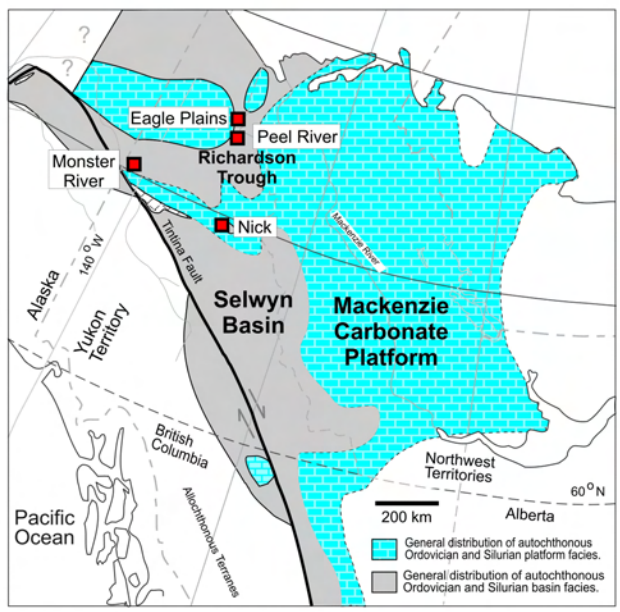

Fig. 1 Location map of the northern Canadian Cordillera showing the Paleozoic basinal and platformal facies, and the location of the major nickel-PGE occurrences (modified from Cecile et al., 1997)

GEOLOGICAL SETTING

The Yukon Ni-PGE deposits occur in basin to slope facies sedimentary rocks of the Paleozoic Selwyn Basin and Richardson Trough, Yukon (Fig. 1). The stratigraphy from the base upward consists of the following units (Fig. 2): 1) a light to medium grey coarse-grained clastic unit up to 3 m thick composed of angular to sub-rounded and commonly fractured limestone and dolostone clasts up 1 meter in diameter. This unit, which has been informally referred to as the "ball member" or "boulder unit" (Fig. 3a) , sits on either limestone or shale and is the most distinctive and easily recognized from the air; 2) a black shale unit up to 120 cm thick containing subrounded carbonate and barite concretions that range in diameter from a few cm to 20 cm; 3) the Ni-sulphide layer that is 10-40 cm thick (Fig. 3b); 4) a black thin-bedded chert with shaly partings that is in sharp contact with the underlying sulphides (Figs. 2). The general stratigraphy and sedimentology are remarkably uniform despite deposits being separated by up to 400 km. In one deposit on the south side of the Peel River (Fig. 3a), the mineralization extends for over 1 km along a riverbank.

The age of the Ni-PGE deposits has not been precisely constrained. Conodonts from limestone boulders a few metres below the mineralization in Peel River section WDG94-1A give Pragian, mid- to late-Emsian and Eifelian ages, which represent maximum ages because of the reworked nature of this unit. Radiolarians in black chert 40 cm above the sulphide horizon give an age within the interval mid-Frasnian to early-Famennian. Therefore, the mineralization may coincide with the Frasnian-Famennian mass extinction boundary although this needs to be confirmed with more precise dating.

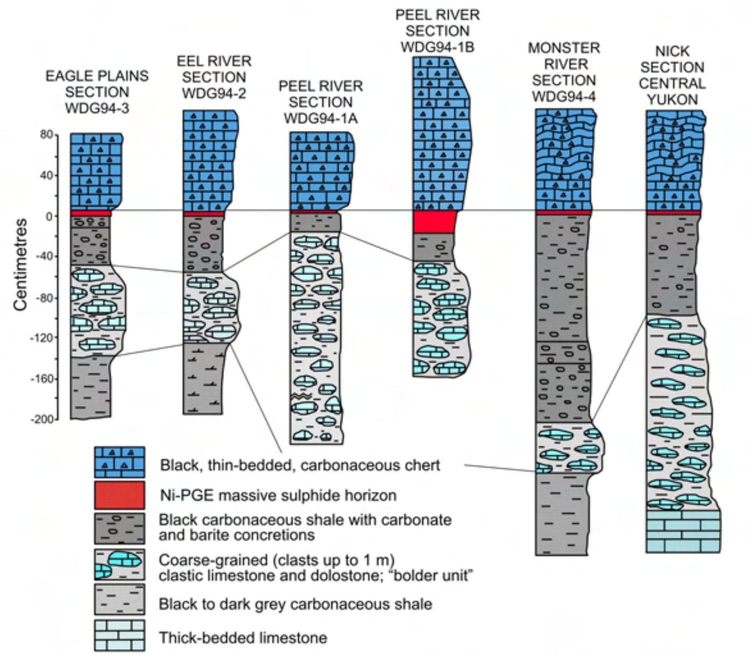

Fig. 2. Correlation of stratigraphic sections spanning the Late Devonian Ni-PGE-sulphide occurrences.

The sedimentary environments are highly varied and are represented by high-energy sedimentation of the "boulder unit" and the deposition of carbonaceous shale and overlying chert under relatively quiescent seafloor conditions. The Ni-PGE sulphides were deposited, therefore, in a low-energy marine environment at or near an abrupt transition from carbonaceous shale to black chert. Redox proxies, such as V/Cr, Ni/Co, V/(V+Ni) and S/C ratios and the absence of bioturbation indicate that the carbonaceous shale and chert were deposited in a marginal anoxic marine basin stratified with euxinic bottom waters.

Table 1. Summary statistics of element abundances for the Ni-sulphide deposits, Yukon

Element	Mean	Min.	Max.	Element	Mean	Min.	Max.
(ppb)				(ppm)			
Pt	298	14.5	511	Zn	6515	230	23000
Pd	109	11.1	202	Cd	21.56	3.2	100
Ru	3.73	0.28	12	Mo	1995	390	3300
Ir	2.26	0.14	10.9	Tl	217	27	390
Rh	0.31	0.027	0.74	Pb	23.35	7	58
Hg	1778	45	5345	Ag	3.36	0.5	8
(ppm)				Ga	11.46	2.8	21
Ni	36941	12000	70000	U	150	3.8	650
Cu	298	89	660	Ba	5564	980	14000
Co	154	35	330	Bi	0.18	0.1	0.3
V	314	5	2100	Ge	0.49	0.1	1.5
Cr	131	42	280	Te	0.26	0.2	0.5
As	6037	646	10690	Sr	426	85	2200
Sb	199	38	390	Y	191	5	1000
Se	2856	210	5700	Yb	9.28	2.3	37
P_2O_5 (%)	1.45	0.01	7.49				n = 17

MINERALIZATION

The sulphide unit (Fig. 3b) displays what appears to be bedding textures that may have been disrupted, perhaps by dewatering of organic-rich sediments during compaction. The mineral assemblages are remarkably uniform between the various occurrences and consist mostly of pyrite, marcasite, vaesite (NiS_2), gersdorffite (NiAsS), millerite (NiS), sphalerite, barite and apatite. The dominant host for Ni is vaesite. The micro-textures are very unusual and distinctly different from those observed in ancient SEDEX and VMS deposits, and sulphides now forming on the modern seafloor.

They commonly display a “cellular” morphology consisting of oblate structures filled by quartz and pyrite and surrounded by an interconnected network of Ni-sulphides, mostly vaesite (Fig. 3c). Elsewhere,

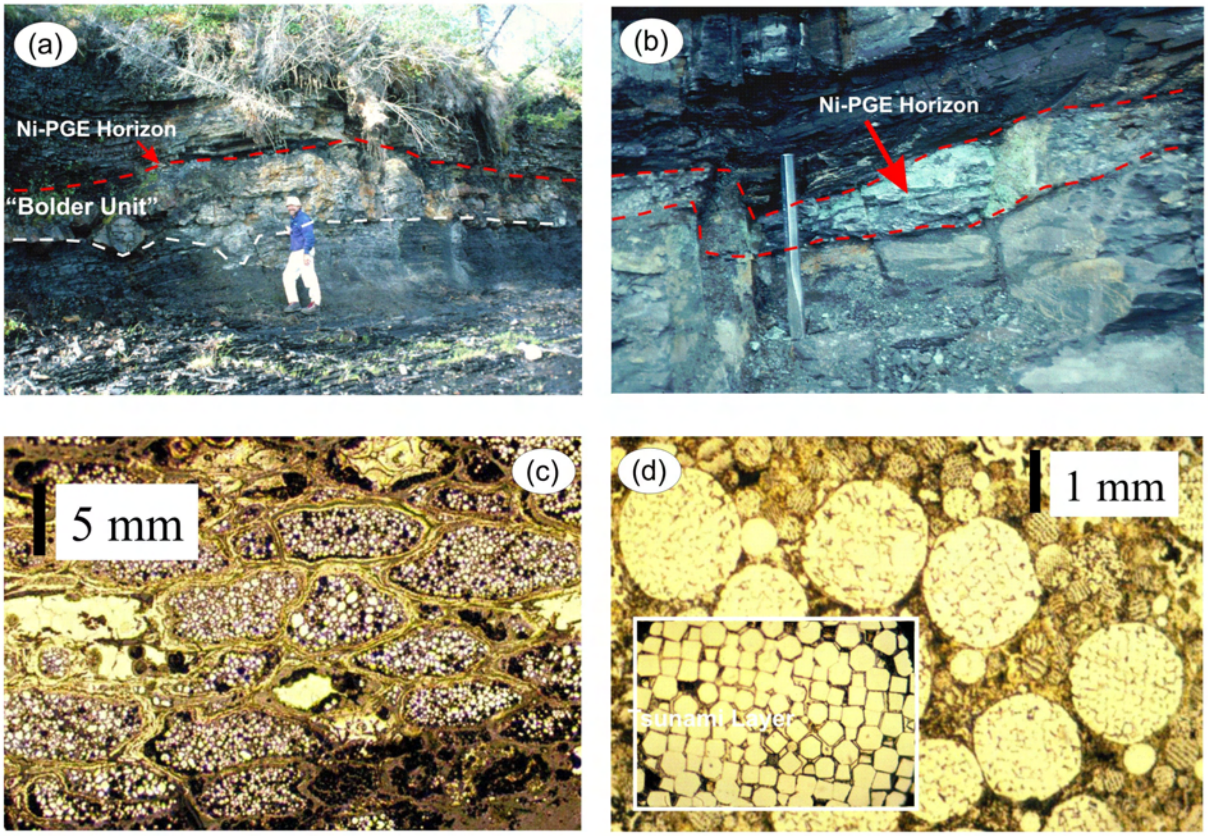

Fig. 3 Nickel-PGE sulphide deposit, Peel River, Yukon. (a) Mineralized horizon underlain by 120 cm thick “bolder unit” composed of poorly sorted, rounded to angular limestone and dolomite clasts; (b) Close-up photograph of the Ni-PGE horizon with green staining at the contact between black shale and overlying bedded chert; (c) Cellular morphology consisting of oblate structures filled with quartz and pyrite and surrounded by Ni-sulphides, mostly vaesite; (d) Framboidal pyrite ranging up to 2 mm in diameter and displaying a cross-hatch or “shreddies” texture.

framboidal pyrite ranging in diameter from 10’s of microns to 2 mm across are characterized by a cross-hatch texture (Fig. 3d). Pyrite framboids are locally replaced by massive pyrite.

Geochemical profiles of the Peel River section WDG94-1B (Fig. 4) display a marked increase in a large suite of siderophile, chalcophile and lithophile elements (i.e. Fe, S, P, Ni, Cu, Pt, Pd, Ir, Ru, Zn, Mo, As, Sb, Se, Co, Cr, V, Cd, Ga, Ag, Tl, Y and Yb) in the sulphide layer and this occurs in all sections. Maximum values are as follows: S (28.9 wt.%), Fe (21 wt.%), Ni (7.0 wt.%), Zn (2.3 wt.%), As (1.06 wt.%), Mo (0.33 wt.%), Se (5700 ppm),V (2400 ppm), Cu (660 ppm), Sb (389 ppm), Co(330 ppm), Cr (280 ppm), Pt (511 ppb), Pd (202 ppb), Ru (12 ppb) and Ir (10.9 ppb), Hg (5545 ppb), Ga (27 ppm), Tl (390 ppm), Ag (8 ppm), and Y (1000 ppm) (Table 1). Total organic carbon (TOC) and P_2O_5 range up to 7 and 7.49 wt %, respectively, in the mineralised interval. The Ru/Ir ratios are chondritic (near 1.0) and indicative of a primitive source.

GENETIC MODELS

The genesis of Ni-PGE sulphide deposits hosted in carbonaceous shales is poorly understood. As a result, several genetic model, invoking a range of hydrothermal, phosphogenic and diagenetic processes in reduced basins, have been proposed but none of these explain all the features documented for this style of mineralization. Clearly, any viable model must explain not just some of the features but all the rather distinctive characteristics of these deposits. These include the widespread geographically distribution of these deposits, not only in the Late Devonian of the Selwyn Basin and Richardson Trough but also in the Early Cambrian of southern China. In the Yukon, the mineralization has been discovered at the same stratigraphic interval over a distance of approximately 400 km. And during a helicopter survey in 1994, at every location this stratigraphic sequence was exposed at the surface, the Ni-sulphide horizon was present. And except for small thickness changes in the "boulder" and overlying shale unit, the stratigraphic sequence is virtually identical in all areas. Clearly, any genetic model would have to explain the underlying high-energy clastic unit, the lateral extent of the mineralization, and the mineralogical and geochemical uniformity in all occurrences. Based on these parameters alone, it is highly unlikely that these deposits originated from a point source of metals such as hydrothermal seafloor vents. Deposits formed from vent fluids, for example SEDEX and VMS deposits, are typically geographically restricted, highly zoned and underlain by a vent complex cutting hydrothermally altered rocks. Furthermore, relatively immobile elements such as Ir and Ru are difficult to transport by hydrothermal fluids.

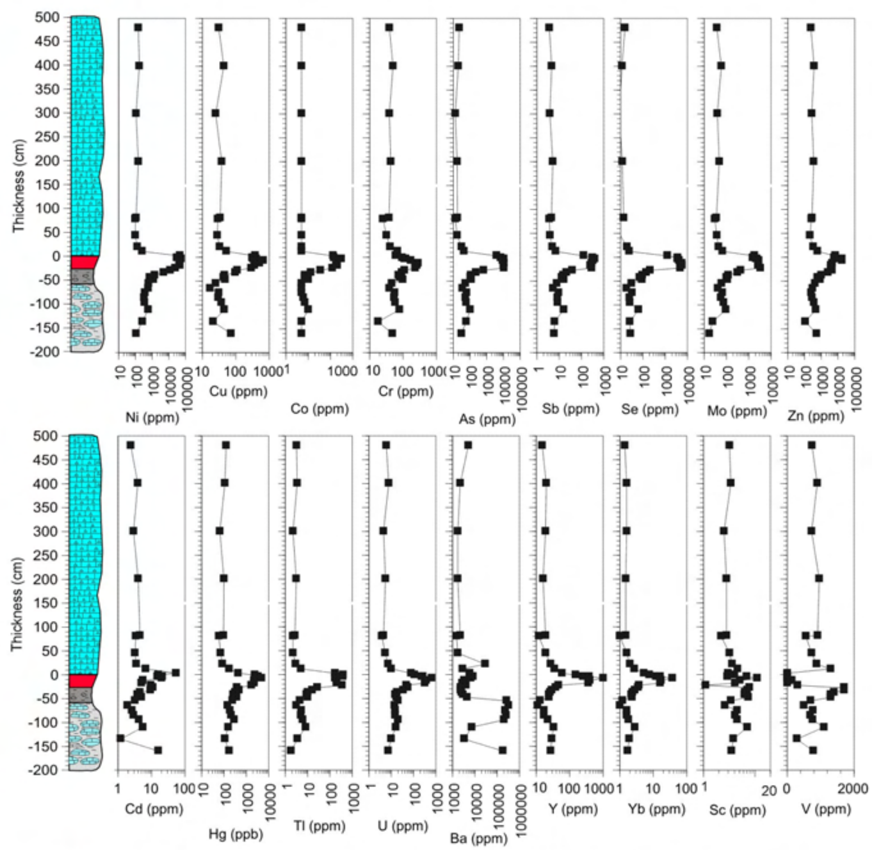

Fig. 4 Geochemical profiles for section WDG94-1B, Peel River, Yukon

However, the widespread distribution of Ni-rich sulphides combined with chondritic Ru/Ir ratios are consistent with a cosmogenic origin that involved the raining of glass particles, quenched from volatized meteorite and target rock, to the seafloor. The suite of platinoid and siderophile elements is similar to that documented for numerous K-T boundary sections and impact ejecta layers. The prevalence of Ni-sulphides was probably controlled by the limiting effect of H_2S on the build-up of dissolved iron in the ambient reduced water column and the seeding of this column with Ni and other metals of meteoritic and crustal origin that settled to the Earth's surface following meteoritic impact. Only under these unusual euxinic water column conditions could Ni^{2+} compete with Fe^{2+} for reduced sulphur and precipitate Ni-sulphides. Although the carrier phases for PGEs have not been identified, they may occur with other meteoritic components (e.g., Fe, Cr, Ni) in microtektites and have been subsequently altered during diagenesis and burial metamorphism.

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Use of high-resolution geophysical data to help mineral exploration and geological mapping in the Abitibi Greenstone Belt

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ABSTRACT

The Abitibi Sub-Province includes many volcano-sedimentary assemblages and large granitic intrusions. It extends from Timmins in Ontario to Chibougamau in Quebec (Goodwin and Ridler, 1970; Goodwin, 1977). Its approximate shape is that of a 800 km long and 240 km wide lozange. About 90% of its surface is covered by glacial deposits and in many areas outcrops are scarce. Overburden thickness can be as much as 50 m to 100 m in the clay belt north of Lake Abitibi making geological mapping difficult and hampering mineral exploration. In the early 1950's regional aeromagnetic surveys were flown by the Geological Survey of Canada (GSC) to help geological mapping and mineral exploration. Line spacing was 800 m and flight elevation was 300 m. Even if the resolution of those surveys was much less than modern surveys they were very helpful, especially in areas with few outcrops. In these years the region was also covered by regional gravity surveys at a station spacing varying from 10 km to 15 km depending on access (Dominion Observatory, 1966). These surveys only allow to map large scale features. In some parts of the Abitibi Belt the governments of Ontario and Quebec have added stations at a sampling varying between 500 m and 2 km to allow a better 3D interpretation of specific geological structures. Following the discovery of the Heath Steele deposit in New Brunswick by an airborne electromagnetic (AEM) survey in 1954 (Fountain, 1998), AEM surveys were intensively used in the search for volcanogenic massive sulfides (VMS) deposits. In the Abitibi, this led to some major discoveries (Pemberton, 1989). The Selbaie (Reed, 1981) and Lemoine deposits are good examples. Because of the success of AEM surveys the governments of Ontario and Quebec flew numerous AEM surveys to promote and help mineral exploration in the Abitibi Belt. The whole region is now covered by AEM surveys, most of them being time-domain EM (TDEM) surveys flown at a line spacing of 200 m and a height of 120 m. Some helicopter-borne frequency-domain EM surveys were also flown. New state of the art geophysical surveys were done over specific areas to assist mineral exploration. Techniques were selected on the basis of the problems to be solved. Aeromagnetic surveys were flown in support of geological mapping and gravity surveys to map structures at depth. TDEM surveys were flown in areas of high mineral potential where only old EM data were available. Seismic data donated by the industry were reprocessed to improve the 3D geological model of the Noranda mining camp (Bellefleur et al., 2007). In addition Xstrata Zinc, Mines d'Or Virginia inc and Campbell Resources have donated to the Ministère des Richesses naturelles et de la Faune (MRNF) and the GSC a series of TDEM data surveys (MEGATEM) flown for them over large prospective areas of the Abitibi Belt since 2000. The location of the geophysical surveys is shown in figure 1. Here, only some of the results will be discussed in detail.

Ground gravity data were acquired by the GSC and MRNF over the part of the Blake River Group and the Matagami mining camp. In both cases the average station spacing was 500 m, however there is lack of data in some small areas due to access problems. The objective of the Matagami survey was to provide new constraints for the stratigraphy and the geology of the survey area and help provide new VMS exploration targets. The survey area is located west of the south flank of the Galinée anticline, a fertile VMS zone. The gravity data suggest that the key tuffite, the fertile horizon with which most VMS are associated, is closer to the surface than previously thought in some unexplored areas. Following the results of this ground gravity survey the MRNF flew a gravity survey extending from the ground gravity

survey area to the Ontario border. This survey was flown at a line spacing of 500 m and a height of 150 m. Data from both surveys were merged together and the first vertical derivative of the Bouguer anomaly is presented in figure 2. EM anomalies and VMS locations are also shown. The Watson rhyolite is clearly associated with a gravity low; interestingly the airborne gravity survey was able to detect a small rhyolite body about 10 km south west of Lake Grasset. We note that near the Caber deposit the EM anomaly trend and the magnetic anomalies (not shown) have a roughly east-west orientation while the gravity trend is north-west suggesting new exploration possibilities. Two TDEM surveys (MEGATEM) were flown specifically for the TGI-3 Abitibi project, a first one located in the Chibougamau area and a second one south of Timmins. In addition Xstrata Zinc and Mines d'Or Virginia inc. have donated to the MRNF and the GSC a series of MEGATEM surveys flown over large prospective areas of the Abitibi Belt. These surveys were exclusively flown to search for new buried VMS ore bodies producing a total 85 000 line km of modern TDEM data. Campbell Resources also gave to the project a MEGATEM survey located between two blocks of the Chibougamau survey. Again the line spacing was 200 m or less and the flight height 120 m.

A systematic study of the Chibougamau survey results was done do evaluate the new information provided by modern TDEM system over an area that had been previously flown by older TDEM systems (INPUT) between 1972 and 1978. The simplest metric for comparing surveys is to evaluate the number of anomalies detected by the two systems. Within the study area there are 4000 INPUT anomalies and 5021 MEGATEM anomalies, cultural anomalies being excluded. A second approach is to compare interpreted depths of the EM anomalies from the new survey to what is known about the depth of penetration of the INPUT systems. Interpreted depths were calculated by the survey contractor using an automated nomogram fitting procedure based on the use of an inductively thin vertical plate model in free space. It is found that 1134 anomalies from the MEGATEM survey have their source deeper than 75 m and 463 anomalies are caused by sources deeper than 100 m. In the study area, the depth of penetration of the INPUT system is estimated to be between 75 and 100 m. Even if our results are from interpreted depths, it is likely that many new anomalies originating from deep sources were detected. This does not correspond to the number of new conductors as a given conductor, because of its length, relative to the line spacing, can give rise to more than one anomaly. A third approach is to look at the response of specific conductors. Figure 3 shows the MEGATEM and INPUT anomalies nearby the former Lemoine volcanogenic massive sulphide mine. At Lemoine, mineralization is within an exhalative horizon concordant with the stratigraphy and its dip is 50^{o}-70^{o} north. Mineralisation is mainly composed of chalcopyrite, pyrite and pyrrhotite, which are all highly conductive, and sphalerite that is weakly conductive. The discovery anomaly was a four channel INPUT anomaly. The MEGATEM response is strong on both the X and Z components. The estimated conductance is 16 S and the conductor has a dip of about 60^{o}N. However, to the northeast, the MEGATEM profile suggests that the conductor dips to the south. The mine horizon is known to be cut by faults. In addition, new EM anomalies from the recent survey show that the conductive horizon extends further to the southwest and the northeast. The continuity of the conductor is better defined by the recent survey than by the former INPUT survey. New conductors have also been identified north west of the Lemoine horizon and may be attractive exploration targets.

These new geophysical surveys have helped to improve our geological knowledge in large areas of the Abitibi Belt in addition to helping mineral exploration. The comparison between EM data acquired from surveys flown more than 25 years apart has shown the utility of flying new modern surveys over these areas. The geophysical coverage of the Abitibi Greenstone Belt is unique given that it is the largest and richest Archean greenstone belt in the world. On the other hand, this coverage is not homogeneous as it consists of old and modern surveys. The availability of this unique coverage was only made possible because of the decision by the provincial and federal governments to archive these data. Data from the 1970's are still proving useful and it is therefore essential to properly archive and document recent surveys to maintain their usability in the future years.

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FIGURES

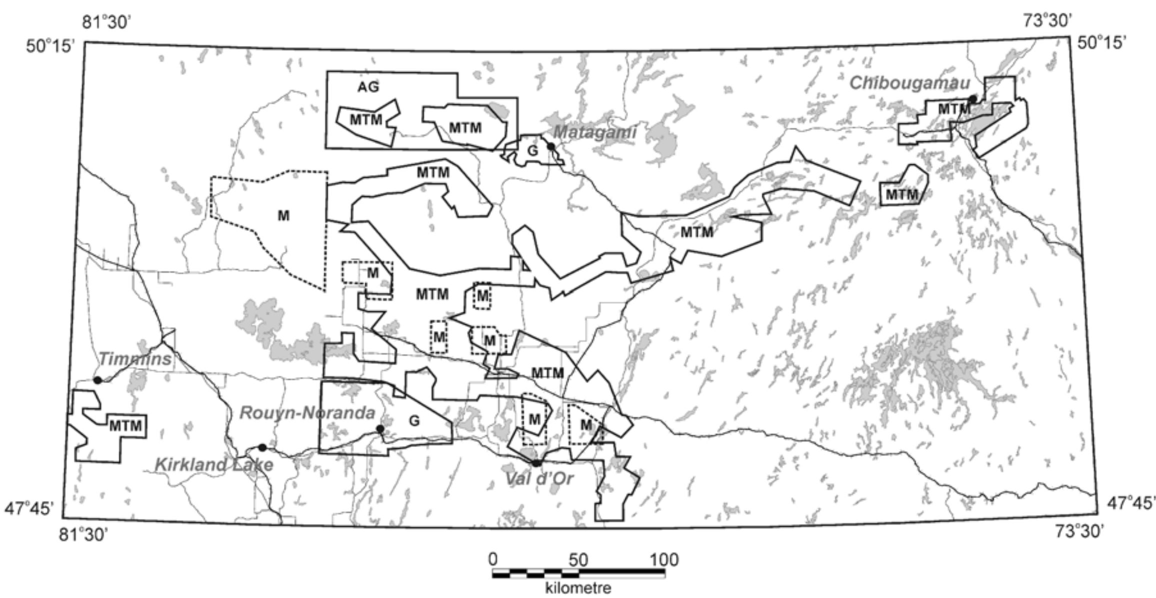

Figure 1. Location of the geophysical surveys: MTM (TDEM MEGATEM survey), AG (airborne gravity), G (ground gravity survey) and M (aeromagnetic survey).

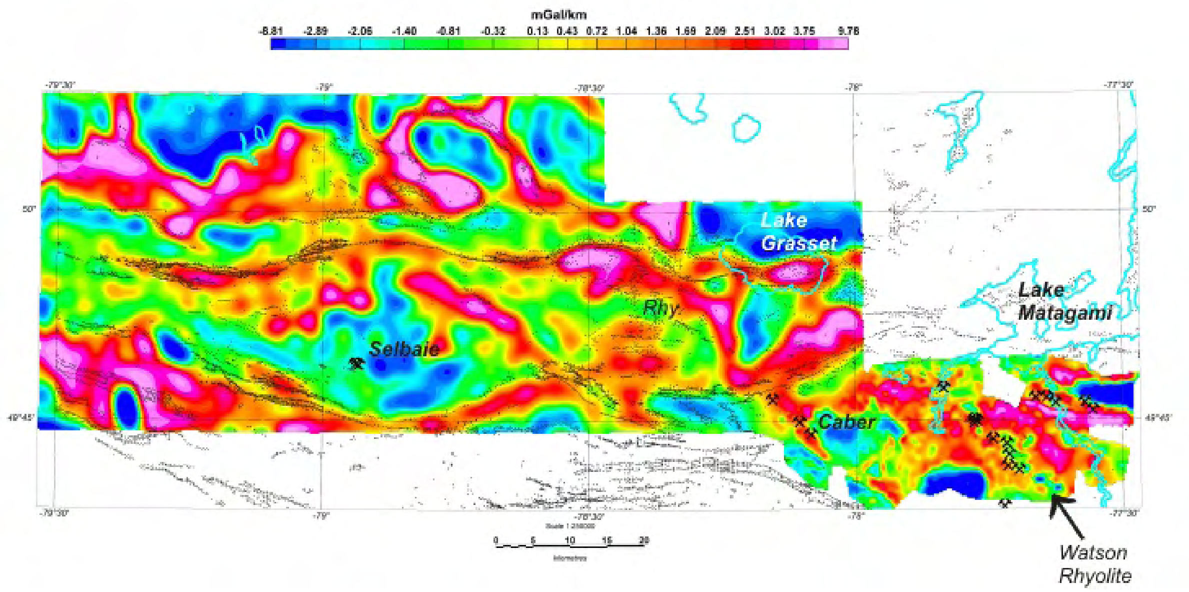

Figure 2. First vertical derivative of the Bouguer anomaly from the ground and airborne gravity surveys. The ground gravity survey is located to the south east of the airborne survey and is characterised by its higher spacial resolution. Black dots are EM anomalies from TDEM INPUT surveys, location of the VMS deposits are indicated.

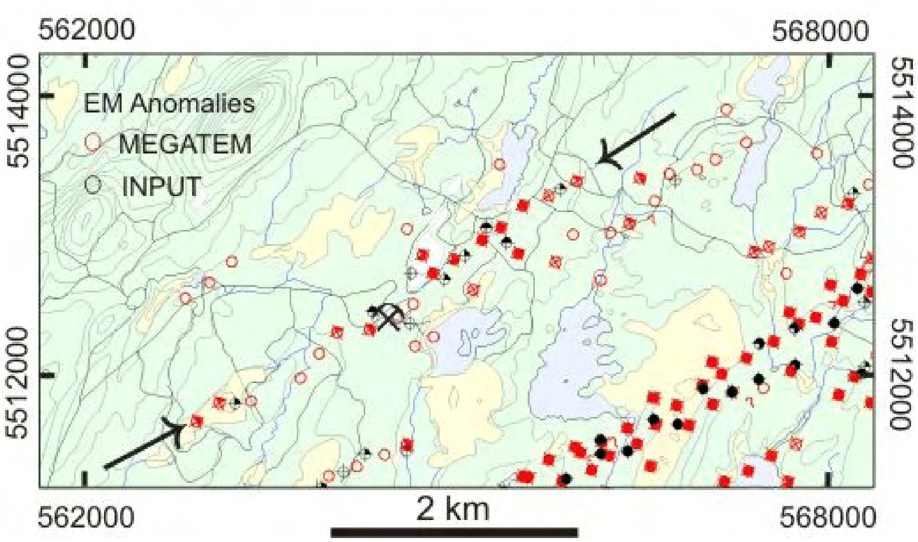

Figure 3. New anomalies along the Lemoine mine horizon. Black arrows point to the horizon. The location of the mine is indicated. MEGATEM anomalies are red, INPUT anomalies black. Note the presence of a second horizon, about 400 m south. This horizon was not detected by the INPUT survey.

Aeromagnetic contributions to geological understanding in TGI-3 Cordilleran study areas

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ABSTRACT

Aeromagnetic data represent perhaps the most important ancillary information in geological mapping projects. Their principal contribution is their ability to "see" through the characteristically ubiquitous veneer of glacial sediments encountered across so much of the Canadian landscape. The importance of this single capability cannot be overstated. And, conveniently, magnetic data are generally readily available in the public domain for most areas of interest. Other significant benefits are the capability to map bedrock beneath bodies of water and basement below sedimentary cover. Magnetic data also provide vectors for ore deposits, and may be modelled to provide insights into the 3rd dimension of the crust. In the TGI-3 Cordillera program aeromagnetic studies have concentrated on the Bonaparte Lake map area, where new high resolution aeromagnetic/radiometric data were collected as part of the program, and the Purcell anticlinorium for which archived high and low resolution data were available.

The focus in the Bonaparte Lake airborne survey was the prospective Quesnel Terrane that includes Triassic-Jurassic volcanic rocks of the Nicola Group and related sub-volcanic plutonic rocks, such as the large Late Triassic to Early Jurassic Takomkane and Thuya batholiths. The western portion of the survey area is covered extensively by a veneer of Miocene-Pleistocene Chilcotin Group basaltic volcanic rocks, and Quaternary glacial cover is ubiquitous. Both types of cover are impediments to exploration of the presumed underlying Quesnel Terrane. Images of the total magnetic field and various derivatives of the field were used in the analysis of the Bonaparte Lake map area. In 1st and 2nd vertical derivative images long wavelength features of the field are eliminated and fine details of the magnetic fabric, which reflects structural fabric, are enhanced. Magnetic domains within the area were defined using all of the magnetic images (Thomas and Pilkington, 2008). Comparison of domain boundaries with geological boundaries revealed close agreement in many cases (Fig. 1), demonstrating that geological units in the area produce characteristic magnetic signatures, and confirming the utility of magnetic mapping. There are, however, instances where agreement is poor, highlighting a need to re-evaluate geological mapping locally. For example, magnetic data support expansion of the Thuya batholith by moving its boundary to include a significant area formerly mapped as underlain by Kamloops Group volcanic rocks, and smaller areas formerly mapped as Chilcotin Group volcanic rocks. The magnetic data also offer perspectives for mineral exploration, as in the case of a domain characterized by narrow linear anomalies crossing the central part of the Thuya batholith. Attention is drawn to its mineral potential via the similarity of its magnetic fabric to that of the

eastern composite, heterogeneous, melanocratic and pervasively altered (propyllitic) portion of the batholith that contains many vein- and fracture-controlled copper mineralization occurrences.

Magnetic signatures can also discriminate between Kamloops Group and Chilcotin Group volcanic rocks. In derivative images the Chilcotin Group is expressed as a variegated pattern of randomly oriented small anomalies having small aspect ratios, whereas the Kamloops Group is associated with anomalies tending to have larger aspect ratios that locally develop a linear magnetic fabric. Ranges of gradient values and amplitudes of high pass filtered residual anomalies over the Kamloops Group are noticeably larger than ranges over the Chilcotin Group (Fig. 2). These criteria indicate that an area mapped as Chilcotin Group south of Bonaparte Lake is actually underlain by Kamloops Group volcanic rocks.

Compilation of a block of 1:50,000 scale geological maps covering much of the prospective Purcell anticlinorium in southeastern British Columbia is being completed as part of TGI-3. It incorporates information acquired from earlier government mapping (generally at 1:50,000 scale), and by Cominco Ltd. (now Teck Resources Ltd.) during an extended period of exploration for Sullivan-type SEDEX deposits. A complementary report on analysis of magnetic data in the compilation area is also being prepared. This will evaluate correlations between geologically mapped units and magnetic signatures, and provide a magnetic framework for future geological mapping and studies, and mineral exploration. High resolution data (400 m line-spacing; 60 m flight elevation) are available in three survey areas (Findlay Creek, St. Mary River, Yahk) collectively covering about one quarter of the area. The entire area is covered by lower resolution aeromagnetic data (805 m line-spacing; 305 m flight elevation) archived in Canada's National Aeromagnetic Data Base. Magnetic signatures in the anticlinorium reflect compositional zoning and marginal phases in igneous intrusions, define unmapped faults, identify unmapped subunits within broader units, and indicate possible repositioning of geologically mapped contacts (Thomas and Brown, 2009). Some insights relating to intrusions are the presence of a marginal phase and several prominent faults within the Mount Skelly pluton and concentric zoning in the small Sanco stock. Concentric magnetic highs characterizing the White Creek batholith are consistent with a pattern of mapped igneous phases, but in detail correlations are variable and invite re-evaluation of some boundaries. Magnetic patterns also indicate a ring-shaped marginal phase near the northern boundary of the compilation area, where no variations in the batholith are mapped. The magnetic images indicate that the Fry Creek batholith is internally more complex than portrayed by geological mapping, which presents it as a single lithological element. The images reveal a somewhat blocky structure with principal elements oriented roughly northwest to north, and also that the batholith includes at least two first order segments associated with different magnetic intensities dissected by some extensive faults.

The higher resolution data from surveys flown at 400 m line spacing and 60 m mean terrain clearance permit definition of finer geological elements, as illustrated by data in the St. Mary River area covering the core and western flank of the anticlinorium. The area is underlain predominantly by metasedimentary successions, and although mapped in some detail, magnetic images outline many additional geological units, and some unmapped faults. These are compared with geologically mapped contacts and faults defined on the new geological compilation in Figure 3. Of particular interest is the large number of linear/curvilinear geophysically-defined units in the western third of the area, where geologically-defined units are generally much wider. Significantly, the geophysical units are parallel/subparallel to geological units, suggesting that geological units comprise several diverse facies or that other distinct (at least magnetically) units have not been recognized by geological mapping. Given the mainly metasedimentary nature of the terrain, the nature of these proposed units is intriguing. Possible candidates for the latter are Middle Creston sedimentary rocks, volcanic units or mafic sills.

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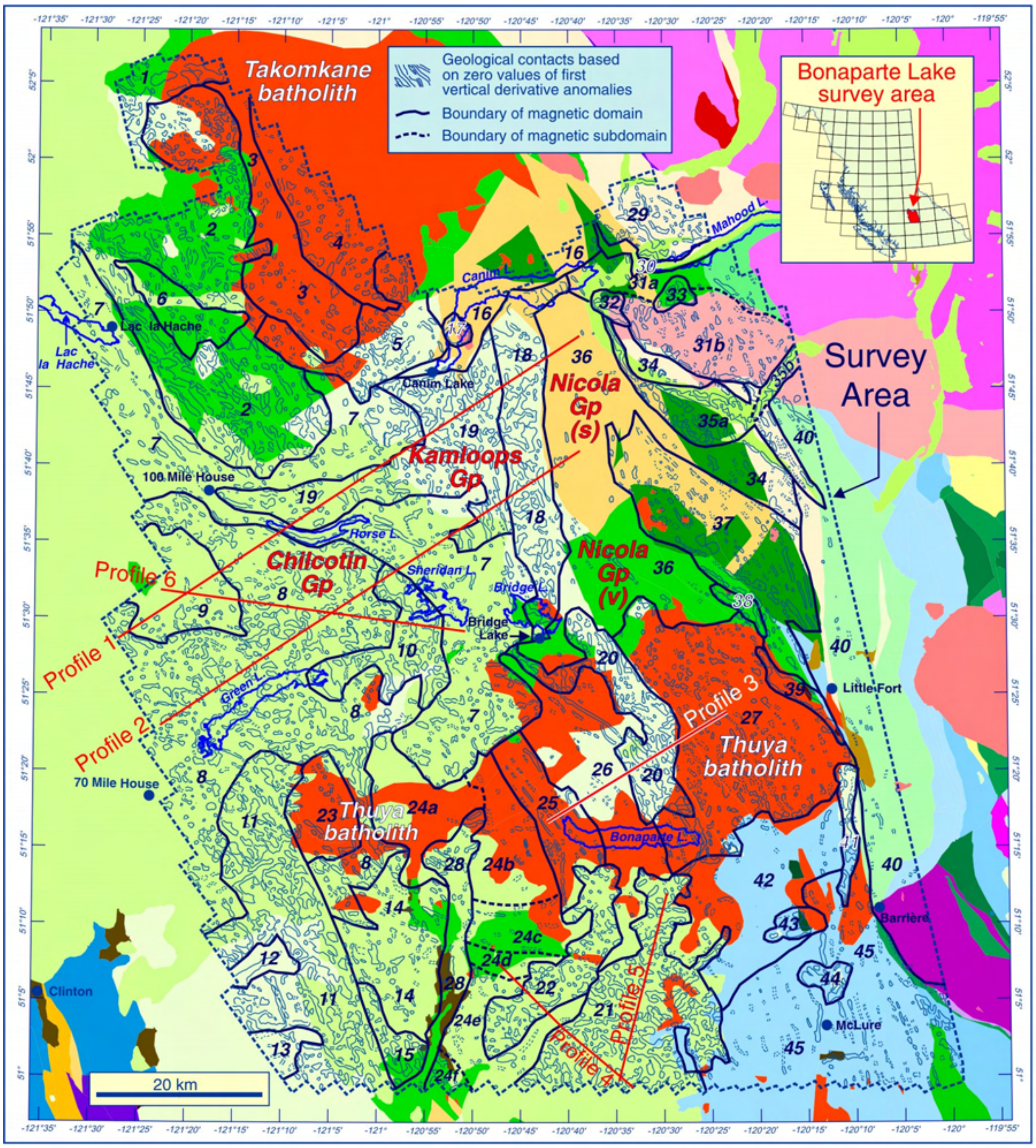

Fig. 1. Geological map of Bonaparte Lake map area with superposed magnetic domains and geological contacts based on vertical derivative anomalies (after Thomas and Pilkington, 2008), and locations of profiles in Figure 2. Nicola Group (s), (v): sedimentary and volcanic units, respectively.

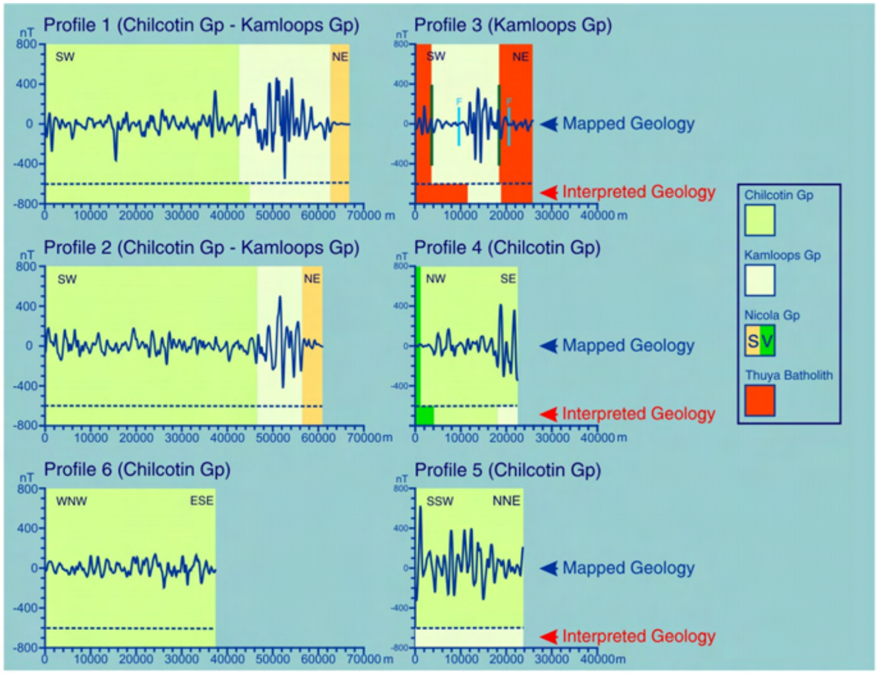

Fig. 2. High pass filtered magnetic anomalies across the Chilcotin and Kamloops Groups. Profile locations shown in Figure 1.

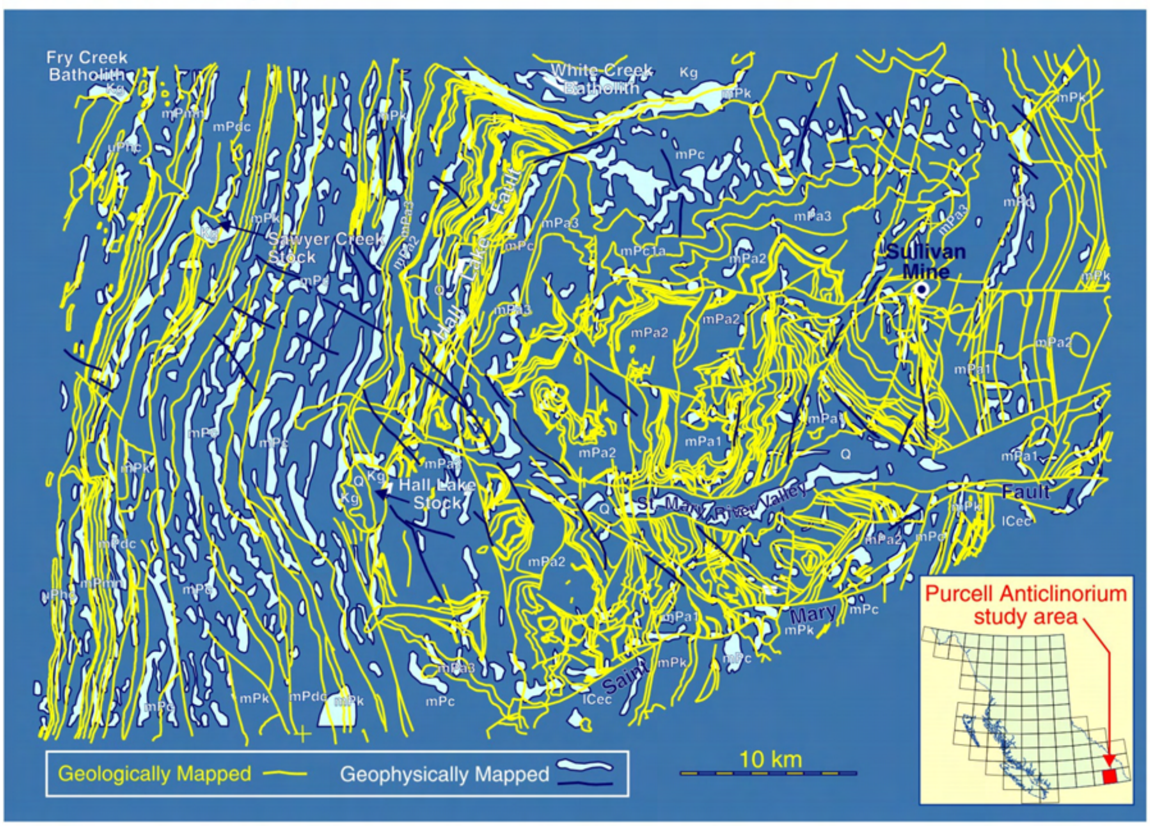

Fig. 3. Comparison of geologically mapped and geophysically mapped units and faults, St. Mary River area. Legend: Q, Quaternary sediments; Kg, Cretaceous Intrusion; lCec, Eager & Cranbrook Fms; uPhc, Horsethief Creek Gp; mPdc, Dutch Creek Fm; mPk, Kitchener Fm; mPc, Creston Formation; mPa(1,2,3), Aldridge Fm (Lower, Middle, Upper). Adapted from Thomas and Brown (2009).

Till indicator mineral and geochemical signatures of magmatic Ni-Cu deposits, Thompson Nickel Belt

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ABSTRACT
Similar to kimberlites, Ni-Cu-PGE deposits have a characteristic suite of indicator minerals. However, very little research has been conducted to document the abundance and chemistry of these minerals in Ni-Cu-PGE deposits and surficial media. To address this knowledge gap, the Geological Survey of Canada (GSC) through its Targeted Geoscience Initiative 3, in collaboration with CAMIRO and the Manitoba Geological Survey collected a suite of bedrock and till samples around Ni sulphide deposits in the Thompson Nickel Belt (TNB). The objective of the study was to characterize the geochemical and mineralogical signatures of Ni-Cu mineralization at the deposit- and camp-scale at varying distances down-ice and to define mineralogical and geochemical background values. The TNB was selected because it hosts several world-class magmatic Ni-Cu deposits, the mineralized zones subcrop and thus were eroded by glaciers, and the presence of a broad indicator mineral dispersal fan defined by Cr-diopside in till that extends up to 300 km southwest of the Belt indicating that the deposits and host rocks should have detectable indicator mineral signatures. The Laurentide Ice Sheet flowed SW across the region from the Keewatin ice centre and then W from the Hudson ice centre and deposited a thin (<3 m) silty sand till which is ideally suited to indicator mineral methods. The region was then inundated by glacial Lake Agassiz, which deposited thick clay and silt, producing a low relief, poorly drained landscape dominated by organic deposits and few bedrock outcrops.

Bedrock (5 kg) and till samples (15 kg) were collected across the northern TNB in 2005 and 2006, most closely spaced around the Thompson, Pipe and Birchtree Ni-Cu deposits. GSC archived till samples collected in the region in 1996 were re-analyzed as part of this study. Bedrock samples were collected from various lithologies within or adjacent to the TNB, and from mineralized and unmineralized ultramafic intrusions. The <0.063 mm fraction of till was analyzed by aqua regia and lithium borate fusion/nitric acid ICP-ES/MS. Gold, Pt, Pd were determined by fire assay/ICP-MS. Bulk till and crushed bedrock samples were processed using tabling and heavy liquid separation to produce ferro- and non-ferromagnetic heavy mineral concentrates. Indicator minerals were examined and counted in the 0.25 to 2.0 mm portion of the non-ferromagnetic and ferromagnetic fractions. Indicator mineral chemistry was determined using electron microprobe analyses (EMPA) and laser ablation ICP-MS to confirm visual identification and document trace element signatures. The <0.25

mm non-ferromagnetic fraction of one metal-rich till sample from the Thompson deposit was further processed using hydroseparation techniques (HS) on the <45µm, 45-75µm, 75-150µm and 150-25µm fractions to concentrate ore minerals, and examined using Mineral Liberation Analysis (MLA) to document the presence of fine grained platinum group minerals (PGM).

A well-developed indicator mineral signature (1000s to 10,000s of grains) occurs in till proximal (<1 km) to the sulphide mineralization. Ni-Cu mineralization indicator minerals include pentlandite, pyrrhotite, chalcopyrite, pyrite, arsenopyrite (Fig. 1), sperrylite, millerite and loellingite. Of these minerals, chalcopyrite and sperrylite are the most likely to survive glacial transport and subsequent surficial weathering and thus will be the most useful for regional exploration. Indicators of potentially fertile ultramafic intrusions include chromite, Cr-diopside, forsterite, enstatite and Cr-corundum. Chromite and Cr-diopside (> ~1% wt.% Cr_2O_3) in till are most abundant in till samples proximal to mineralization.

Magnetite trend chromites in bedrock have elevated Zn contents (>2 to 18 wt.% ZnO) that are restricted to mineralized bedrock at the Thompson, Birchtree and Pipe deposits and proximal (<500 m) till samples. Zn-rich chromite was expected as other researchers have reported its presence in TNB deposits, as well as other magmatic Ni-Cu deposits around the world. Zn enrichment in chromite in the TNB ores is likely related to the high grade of metamorphism that has affected the belt and can be used as a vector to mineralization in the TNB. A preliminary evaluation of the usefulness of iron oxide minerals as an indicator of Ni-Cu-PGE mineralization was also carried out as part of this study. A significant number of randomly selected iron oxide grains from the ferromagnetic fraction of three metal-rich till samples plot in the Ni-Cu-PGE field of a Ni+Cr vs Si+Mg discrimination diagram suggesting that the abundant, robust iron oxides that are routinely recovered from till may be useful indicators of the presence of Ni-Cu mineralization. MLA of four HS concentrates from till sample 05-MPB-010 revealed the presence of various PGM (Fig. 2). These results indicate that the <0.25 mm fraction of till concentrates, often set aside because the grains are too small to visually examine, can be examined for the presence of fine grained ore minerals, especially PGM that usually occur in the silt size range.

The physical appearance of olivine and chromite, indicators of Ni-Cu-PGE and kimberlite, can be used to distinguish between the deposit types. Olivine grains in TNB rocks and till are smaller, paler to colourless (pale yellow to pale green in kimberlite) (Fig.1) and contain inclusions of Cr-magnetite or Fe-chromite which impart paramagnetism (kimberlitic olivine is nonparamagnetic). Chromite in TNB rocks and till exhibit sharp edged grain morphology (Fig. 1) in contrast to kimberlitic chromite which often displays resorbed surfaces.

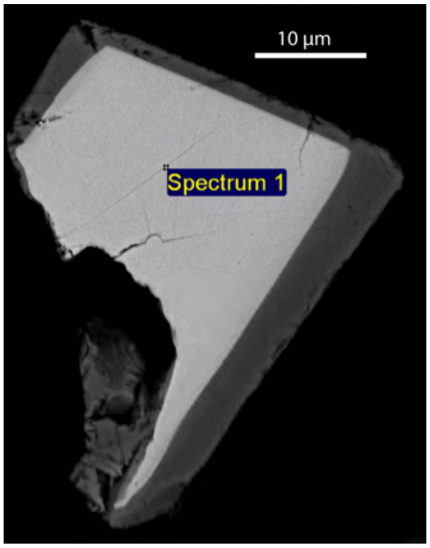
Ni-Cu ores in the TNB are dominated by pentlandite, pyrrhotite, pyrite and millerite and thus local metal-rich till is Ni-rich (up to 3760 ppm) and to a lesser extent Cu-rich (up to 215 ppm) TNB ore also contains Te, As, Sb, Co, Cd, Se and Bi-bearing mineral species, which are likely the source of elevated concentrations of these elements in till proximal to the deposits. A variety of PGE minerals occur in the ores and are the source of the elevated Pd (up to 98 ppb) and Pt (up to13 ppb) concentrations in till. Using these pathfinder elements, anomalous till samples in remote locations collected as part of the 1996 regional survey were identified, and may indicate the presence of previously unknown Ni-Cu mineralization.

Figures:

Figure 1. Ni-Cu indicator minerals from bedrock and till from the Thompson and Pipe deposits: a) 1-2 mm pyrrhotite grains from the ferromagnetic fraction of till sample 05-MPB-014 at the Pipe deposit; b) 0.5-1.0 mm pentlandite grains from till sample 05-MPB-010 at the Thompson deposit; c) 0.25-0.5 mm arsenopyrite grains from till sample 05-MPB-010 at the Pipe deposit; d) 0.5-1.0 mm chalcopyrite grains from till sample 05-MPB-009 at the Thompson deposit; e) 0.25-0.5 mm pyrite grains from till sample 05-MPB-009 at the Thompson deposit; f) 0.25-0.5 mm chromite grains from till sample 05-MPB-013 at the Pipe deposit; g) 0.25-0.5 mm olivine grains from till sample 05-MPB-014 at the Pipe deposit; h) 0.25-0.5 mm Cr-diopside grains from till sample 05-MPB-013 at the Pipe deposit. Scale bars are 1 mm apart.


a)
b)
c)
d)
e)
f)
g)
h)

Figure 2. SEM image of grain of irarsite (light grey) with hollingworthite outer zone (darker grey) found in the <45µm fraction of the heavy mineral concentrate of till sample 05-MPB-010 from the Thompson deposit.



Ice-flow history and till geochemistry of the Bonaparte Lake map area, south central British Columbia

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ABSTRACT

At the onset of the Late Wisconsinan Fraser Glaciation, ice advanced from the Cariboo Mountains to the west and southwest within the Bonaparte Lake map area of south central British Columbia. As glaciation intensified, ice from the Coast and Cariboo mountains coalesced over the Interior Plateau resulting in the development of an ice divide north of the map area from which ice flowed to the south. These two general phases of ice flow influenced glacial transport over this region as illustrated by the distribution of terbium in till west and south of the Raft Batholith. Consequently, tracing the source of high gold content of till near the northern edge of the Thuya Batholith will need to take into account these two vectors of glacial transport.

INTRODUCTION AND SETTING

A surficial geology mapping and regional till sampling project was completed within the Bonaparte Lake map area (National Topographic System - 092P), south central British Columbia. This project is part of the Mountain Pine Beetle Program of the Geological Survey of Canada, with the objective of stimulating mineral exploration and diversifying the economy of this region severely impacted by mountain pine beetle infestation. The map area dominantly lies within the Interior Plateau of British Columbia and is surrounded by the Coast Mountains to the west and the Cariboo Mountains to the northeast (Fig. 1). The map area is underlain by Upper Paleozoic to Lower Mesozoic arc volcanic, plutonic and sedimentary rocks of the Quesnel Terrane juxtaposed to the east with rocks of the Slide and Kootenay terranes. Late Triassic to Cretaceous granitic rocks intrude these terranes. These basement rocks are overlain in large part by Tertiary and minor Quaternary volcanic rocks with minor sedimentary rocks. The region is covered by variable thicknesses of glacial sediments deposited during the Late Wisconsinan Fraser Glaciation. Field work was completed during the 2007 and 2008 field seasons resulting in a revised interpretation of the ice-flow history which is now utilized to interpret the till composition data (geochemistry and mineralogy).

ICE-FLOW HISTORY

Our interpretation of the ice-flow history builds on the model first suggested by Tipper (1971a; 1971b) and takes into account the studies completed west of the map area by Lian (1997) and Lian and Hicock (2000). At the onset of the last glaciation, glaciers first formed in the Cariboo Mountains to the northeast and the Coast Mountains to the west. The first glacial ice to reach the region was derived from the Cariboo Mountains and flowed to the west and southwest (yellow arrows on Fig. 2). As the Fraser Glaciation intensified, glaciers from the Coast and Cariboo mountains coalesced over the Interior Plateau, forming an ice divide north of the Bonaparte Lake map area forcing ice to flow progressively to the south throughout the region (blue and green arrows on Fig. 2).

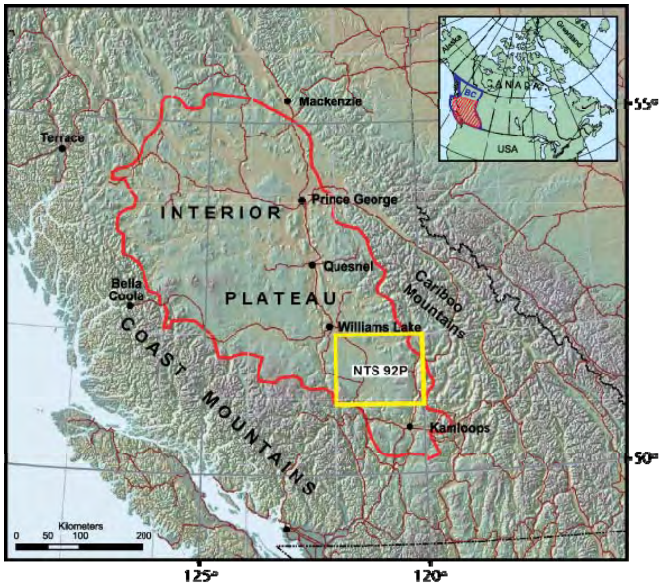

Figure 1. Bonaparte Lake map area (NTS 92P) in British Columbia (yellow box). The red line outlines the region impacted by mountain pine beetle as identified by the British Columbia Ministry of Forests in 2007.

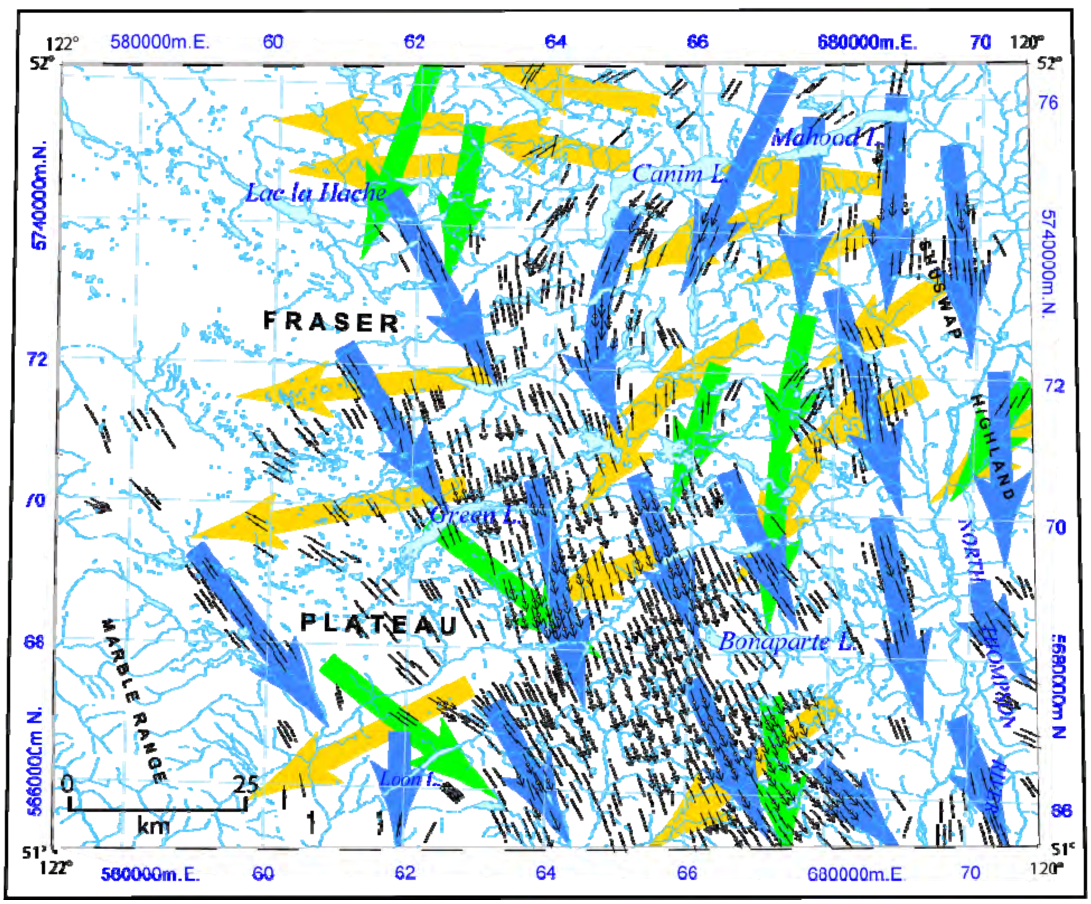

Figure 2. Ice-flow history of the Bonaparte Lake map area. Modified from Plouffe et al.(2009; 2010). Drumlins, flutings and crag-and-tails (black lines and arrows) are from Tipper (1971a). Ice flow at onset of glaciation shown with yellow arrows. Ice flow during ice build-up and glacial maximum shown with green and blue arrows.

TILL GEOCHEMISTRY

Data on till composition including till mineralogy and geochemistry along with methodologies and interpretation are reported in Plouffe et al. (2009; 2010). Two examples are extracted from these reports to illustrate: 1) the impact of glacial transport on till composition, and 2) the high potential for the discovery of gold mineralization at the north end of the Thuya Batholith.

Terbium concentrations in the heavy mineral concentrates (HMCs) of till (S.G. > 3.2; <0.250 mm) determined by instrumental neutron activation analyses (INAA) show a strong enrichment (>98th percentile) over the Raft Batholith and moderate levels (>90th) over the Thuya and Takomkane batholiths (Fig. 3). High concentrations (generally exceeding the 90th percentile) extend to the west and southwest of the Raft Batholith. Furthermore, terbium concentrations >95th percentile extend south of the same intrusion in the Clearwater area (Fig. 3). This distribution of terbium concentrations in till is interpreted to reflect southwestward and southward glacial transport of debris derived from the Raft Batholith. Other granophile-related elements show similar distribution patterns in till as reported by Plouffe et al. (2010).

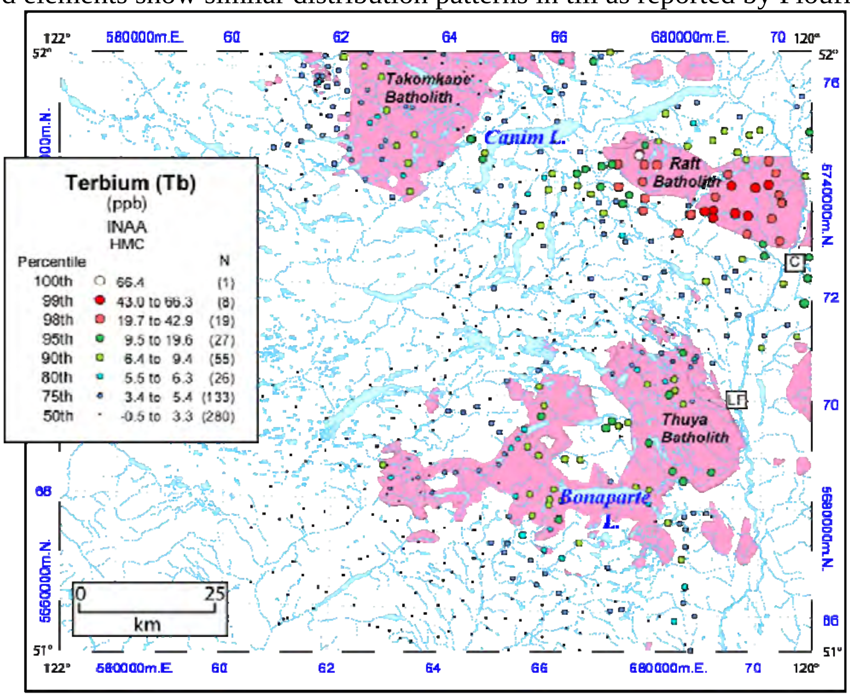

Figure 3. Terbium concentrations in heavy mineral concentrates of till determined by INAA. Simplified outline of major intrusions (pink polygons) from Campbell and Tipper (1971) and Schiarizza et al. (2002a; 2002b). C – Clearwater; LF – Little Fort.

The highest gold concentrations in the silt plus clay sized fraction (<0.063 mm) of till determined by INAA are clustered near the northern edge of the Thuya Batholith (Fig. 4), a multi-episodic intrusion of Late Triassic – Early Jurassic age (Plouffe et al., 2010). Several of the till samples with high gold concentrations also contain high gold grain counts (Plouffe et al., 2009). Some of the sites with high gold levels are located near known mineral occurrences but a number of them are not, and could be related to undiscovered gold mineralization in bedrock. More specifically, three sites with the highest gold concentrations are closely spaced and located approximately 10 km northwest of Little Fort. In this same location, 20 fine-grained, felsic granitoid boulders, which contain high levels of gold and silver (up to 4.15 g/tonne gold and 88.3 g/tonne silver) were discovered previously (Gruenwald, 1992). The presence of mineralized boulders containing anomalous gold and silver concentrations combined with anomalous gold concentrations in till confirm the presence of an undiscovered bedrock mineralized zone somewhere up-ice of this site.

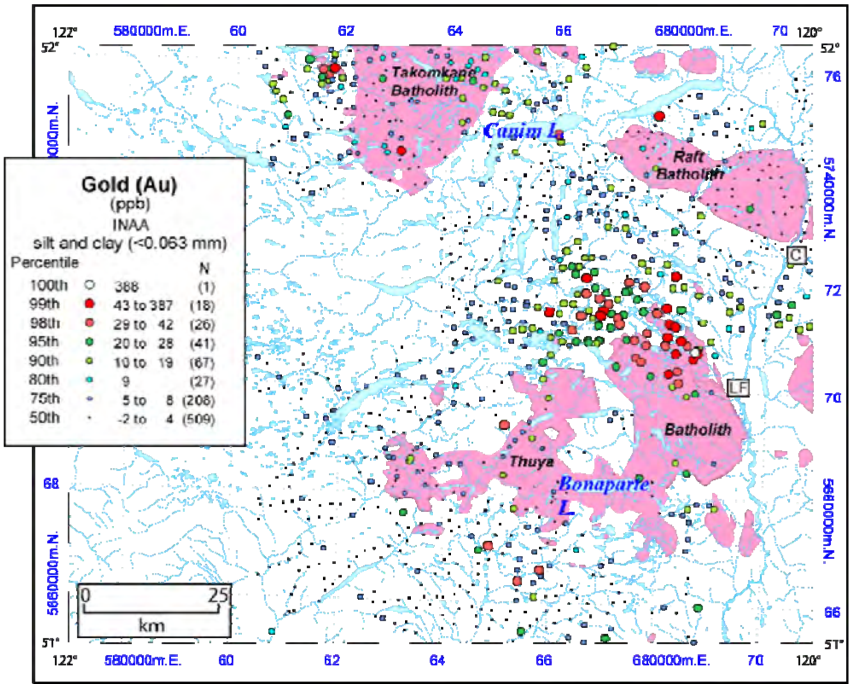

Figure 4. Gold concentrations in the silt plus clay-sized fraction (<0.063 mm) of till by INAA. Simplified outline of major intrusions (pink polygons) from Campbell and Tipper (1971) and Schiarizza et al. (2002a; 2002b). C – Clearwater; LF – Little Fort.

CONCLUSION

A high potential for discovering unknown gold mineralization at the northern edge of the Thuya Batholith in the Bonaparte Lake map area exists based on the till composition of that region. Tracing the bedrock source of the high gold levels in till will need to rely on two general vectors of glacial transport and dispersal: a first one to the west and southwest, and a second one to the south. The impact of these two vectors of glacial transport is well illustrated in the regional distribution patterns of the terbium concentrations in the HMCs of till south and west of the Raft Batholith.

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GeoTour guides and geological highway maps: building a social licence for mining and mineral exploration in southern BC

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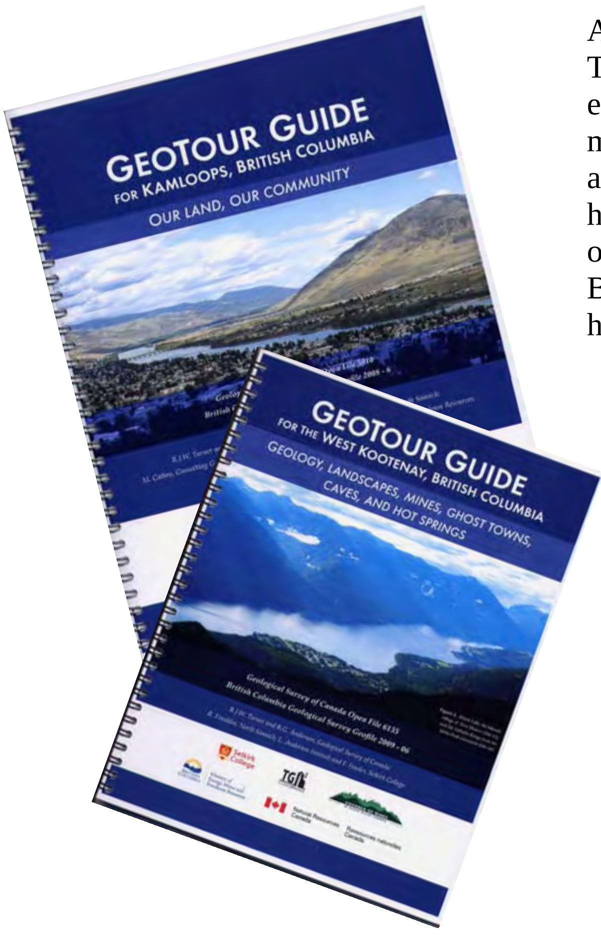

ABSTRACT

The outreach component of the TGI-3 Cordilleran Project enhances the social licence for mineral exploration and mining by empowering partners to tell stories to the public about mines and mining in southern BC, both modern and historic. These stories are embedded within a broader suite of engaging geological stories about the scenery of southern BC such as mountains, rocks, caves, hot springs, and historic buildings.

The stories are presented in **GeoTour guides** for the **Kamloops** (Turner et al., 2008), **West Kootenay** (Turner et al., 2009), and **East Kootenay** areas (Turner et al., 2010)**.** These guides are virtual tours of local features.

The GeoTour guides partners include GSC, BCEMPR, and local groups such as chambers of mines and museums, and high school, college and university educators. GeoTour guides are available free of charge on the internet, or as booklets through local sellers and GSC sales offices.

GeoTour guide content has been used by the authors and partners for public field trips, signage on walking trails, public talks, and in response to information requests. A **Southern British Columbia Geological Highway Map** (in prep) tells similar types of stories across a larger geography, highlighting roadside geological scenery, and intends to reach a much broader audience and distribution through BC Tourist Information Centres throughout BC, and government sales offices.

Outreach products

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GeoTour guide for the **West Kootenay**, British Columbia ; Geological Survey of Canada Open File 6135, 43 pages; also BCGS Geofile 2009-6.

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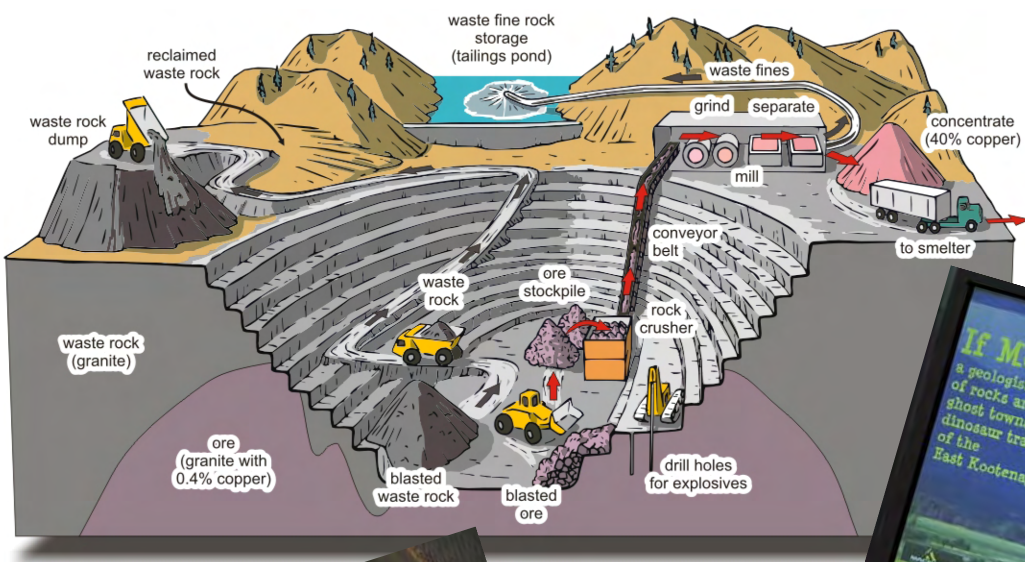

Reconnaissance and Detailed Surveys in Southern BC using Biogeochemical Methods

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SUMMARY

Studies over the past half century have greatly advanced the understanding of biogeochemical processes. Mapping of multi-element patterns in southern British Columbia suggests that, among other elements, Tl and Hg may be biogeochemical pathfinder elements for Broken Hill-type Sedex deposits. The halogens in plants, too, may provide additional vectors toward base metal-mineralized areas. Opportunistic sampling during field mapping projects can add important focus for detailed exploration, and help trace the source of till anomalies. Molybdenum in cedar foliage has outlined the MAX Moly mine area and generated additional targets of similar magnitude of unknown origin. Investigation of one of these in southern BC has resulted in the discovery of low-grade mineralization in rocks exhibiting similar characteristics to the MAX Moly deposit. Moving forward, more emphasis on the distribution of volatile elements (e.g. Hg; halogens associated with fluid inclusions) as well as commodity elements, and an improved understanding of the role of bacteria in mobilizing metals should further entrench the role of biogeochemical methods for assisting in the exploration for mineral deposits.

KEYWORDS: *Biogeochemistry, Exploration, Base Metals, Gold, REE, Molybdenum*

INTRODUCTION

Over the past half century there have been significant developments in the understanding and application of biogeochemical methods to the search for buried mineral deposits – both deep and shallow. It is now apparent that depth of root penetration and relationship of plant chemistry to soil composition are not critical to obtaining subtle biogeochemical responses to deeply buried mineralization. Various processes invoked for explaining partial leach soil anomalies are equally relevant for explaining signatures of elemental anomalies in plant tissues. These include movement by diffusion, electrochemical cells, seismic pumping, artesian flow, and particularly bacterial movements. However, these processes are modified and controlled by plant requirements and tolerances, so that the 'barrier mechanisms' identified by Kovalevsky (1979) come into play and need to be considered when interpreting data from biogeochemical surveys.

A Targeted Geoscience Initiative (TGI-3) project led by the Geological Survey of Canada aims at stimulating base metal exploration activities in south and south-central British Columbia. As part of this project, we have conducted biogeochemical surveys in forested and rolling to rugged terrains with variable thickness of till. In light of past discoveries, the selected study areas remain highly prospective for various types of metal deposits. Results and interpretation of orientation surveys at three sites are summarized below.

Fig. 1. Location of Mabel Lake, Bonaparte Lake, and MAX Mine survey areas..

Mabel Lake Area

A helicopter-supported survey was conducted over 700 km^2 that included the stratigraphic setting of the Kingfisher deposit and similar stratigraphic units that border Tsuius Creek, to collect 562 Douglas-fir tree tops at 1 km spacing. Of five known groups of Zn/Pb deposits within a cover sequence that mantles Palaeoproterozoic core gneiss, mineralization at Kingfisher and adjacent deposits comprises the only group below the tree-line. The widespread regional distribution of thin calcareous units that host these deposits lends credence to the concept that similar mineralization may lie beneath the extensive area that is covered by a veneer of glacial deposits and dense forest.

Analysis of dry twigs revealed areas of Zn enrichment with associated elements (Cd, Tl and Mn) that show a spatial relationship to areas of Pb enrichment (with Fe, Hg, REE, Al, and Ti), especially in an area approximately 500 m south of Tsuius Creek. A strong Pb/Zn zonation is typical of Broken Hill-type Sedex mineralization. Of particular note were localized high Tl values.

Subsequent analysis of the ashed needles from these twigs confirmed the patterns established from the dry twigs. It served to enhance some signatures (notably Ag) and added a layer of data for the halogens, demonstrating a F association. Also from these additional analyses a pattern of Cd and B enrichments at Kingfisher was evident.

Follow-up ground studies involved the analysis of outer bark from western hemlock collected at 100 m sample spacing over the Tl anomaly south of Tsuius Creek. This permitted more clearly defining the extent of the Tl anomaly (600 m x 600 m) and its relationship to other trace elements. Figure 2 shows the Tl anomaly and the spatial relationship of Hg which appears to define a conjugate set of lineaments interpreted as leakage from structural weakness. The multi-element association at this locality suggests that Tl and Hg may be pathfinder elements to concealed base-metal mineralization.

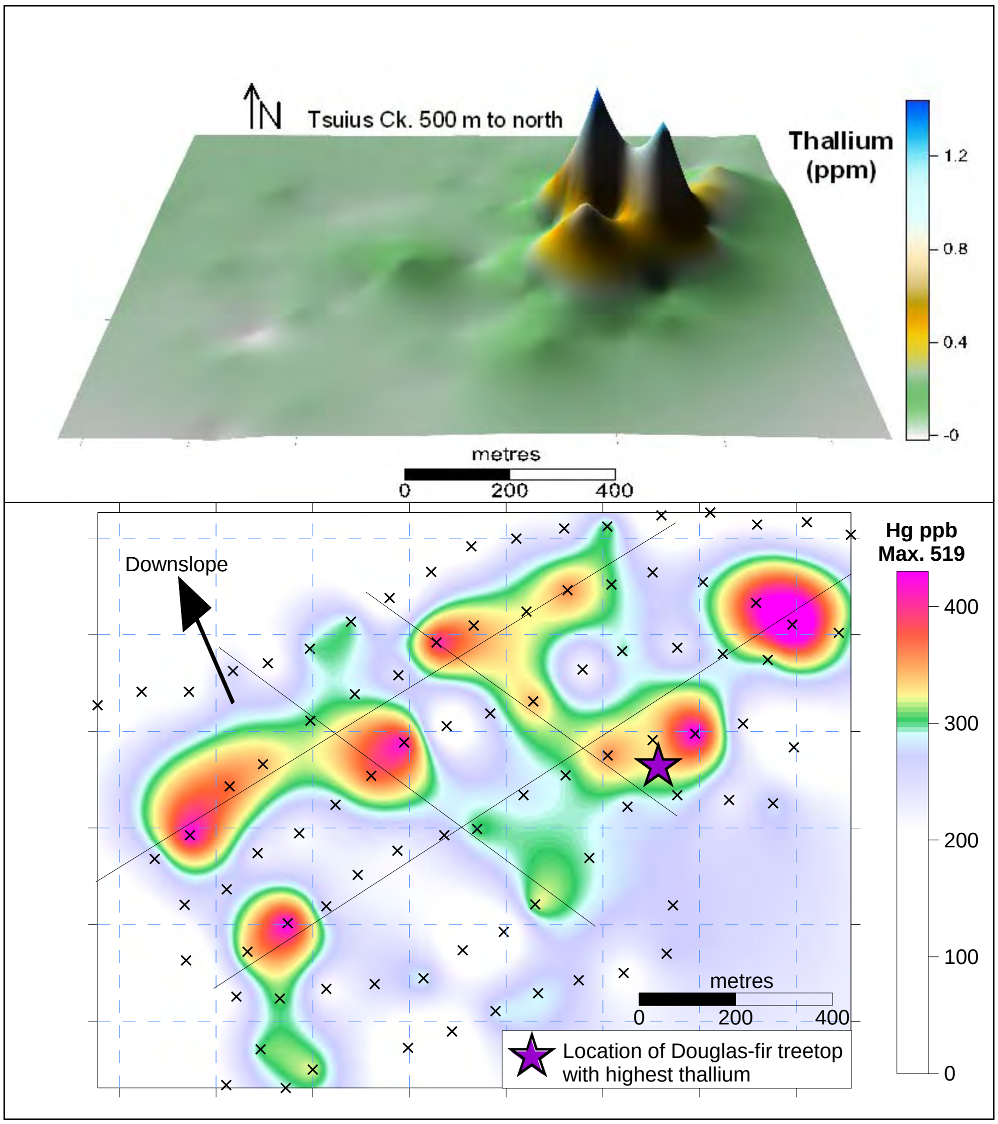

Fig. 2. Thallium (3D plot, viewed from south - top figure) and Hg in dry western hemlock bark – Tsuius Creek, BC (Dunn & Thompson 2009a).

Bonaparte Lake Area (Thuya Batholith)

In the Bonaparte Lake area of south-central BC, five hundred samples of outer bark from Engelmann spruce and lodgepole pine were collected on an opportunistic basis during the course of field mapping. Consequently, the sample distribution was uneven, but expedient and sufficient to provide indications of areas with potential concealed mineralization.

The analytical data provided a basis for comparing and contrasting the geochemical signatures of the two types of bark and defining those elements that generated the same or similar signatures while establishing other elements that generated different distribution patterns because of tolerances to, or requirements for, those elements. Most elements generated similar distribution patterns attesting to the robustness of the biogeochemical method and reinforcing the significance of the signatures (Dunn & Anderson 2009). Elements that tended to show different patterns (e.g., Ba, Sr) were those that were significantly more concentrated in a particular tree species. The pine bark was more enriched than the spruce in Ag, Al, Cd, La, Pb and Sb. Conversely, spruce was more enriched in Ba, Ca, Mn, Rb, Sr, and Zn.

Results from a recent till survey (Plouffe *et al.,* 2009) revealed unusually high concentrations of thorianite grains in the heavy mineral concentrates. Plots of thorianite-related elements – Th, U, and REE – in the conifer bark samples indicate an area of subtle enrichment that is located up-ice from the proven direction of ice movement. This may help to more closely focus on the bedrock source of the thorianite grains in till. Also, multi-element signatures in the bark assisted in identifying known Cu mineral occurrences, delineating areas of Au enrichment and possibly PGE, as well as defining signatures characteristic of the principal plutonic and volcanic units. For example, there are significant increases in Ni, Cr and Co over known and concealed mafic to ultramafic units.

MAX Moly

The MAX property lies near the north end of the Kootenay Arc in tightly folded, strongly sheared Palaeozoic metasedimentary rocks. The reported commodities are Mo, W, Pb, Zn and Cu. The area is heavily forested rugged terrain with outcrop largely obscured by a cover of till. Cedar foliage was collected along several traverses up the steep hillside toward known mineralization.

The location of the discovery outcrop was clearly outlined by Mo in cedar. Two additional Mo anomalies of unknown source and similar intensity were identified (Fig. 3). In mid-2008, Roca Mines drilled two drill holes, 100 m apart that targeted the northern biogeochemical anomaly. They reported "*Intense silicification, hornfelsing, locally strong quartz veining, and pervasive sericite alteration with trace molybdenite throughout….reminiscent of the MAX resource itself where the extent of a relatively minor molybdenite mineralized zone on surface lies atop a large-scale mineralized deposit currently being mined.*" Roca Mines press release, 12th August 2008 (www.rocamines.com).

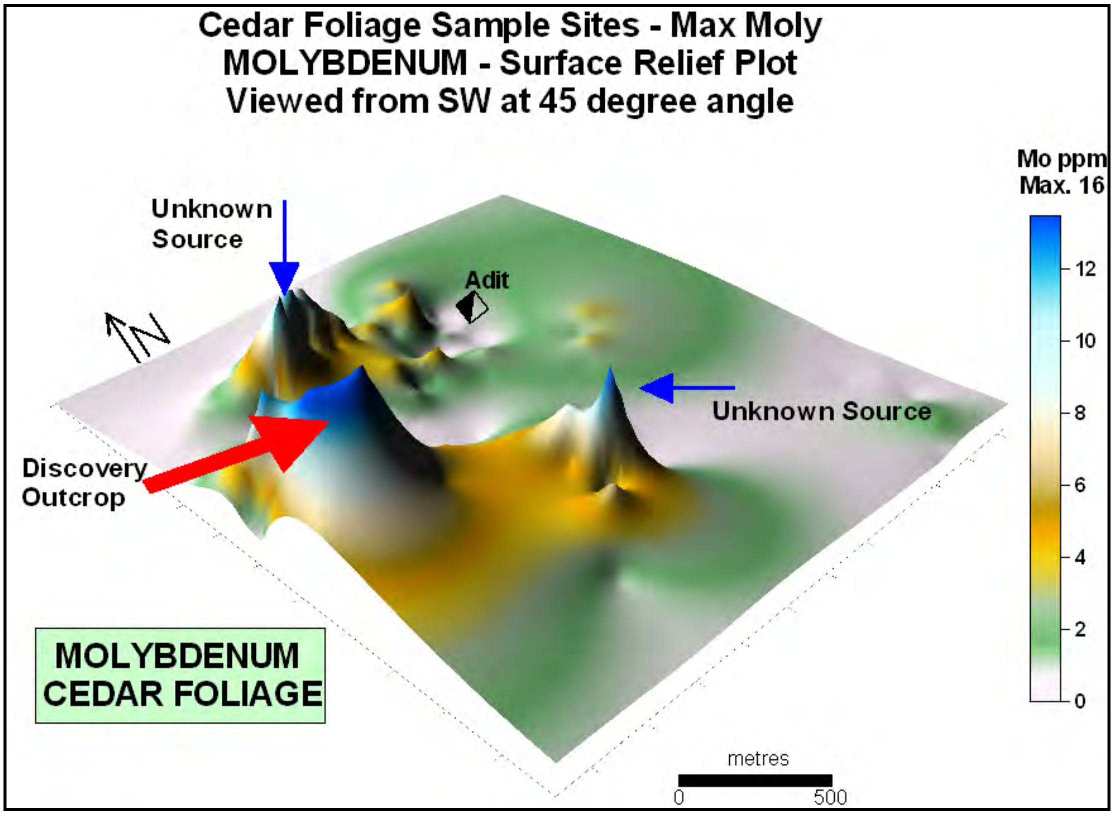

Fig. 3. 3D plot of Mo in cedar foliage. MAX Moly mine (Dunn & Thompson 2009b).

CONCLUSIONS

(1) Examination of data from past biogeochemical surveys in context of subsequent discoveries has established their relationship to mineralization.
(2) Pathfinder and commodity element distribution patterns from recent surveys have delineated new targets for base metals and other commodities, and resulted in new discoveries.
(3) It is anticipated that focus on volatile elements (especially halogens and Hg) and improved understanding of processes (notably bacteria) in mobilizing metals from depth will provide further successes for biogeochemical surveys.

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ESS Contribution number: 20090401

Distribution and Thickness of Volcanic and Glacial Cover on the Interior Plateaus

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Mineral and energy resource exploration in central British Columbia has been hampered by the commonly extensive and indeterminably thick cover of Neogene basalt lava and Quaternary sediment, leading a dearth of new exploration and discoveries. New geological, volcanological, and geospatial studies focused on the Chilcotin Group lavas, and to a lesser extent the Quaternary drift, indicate strongly that the lateral extent and thickness of the cover is significantly less than previous estimates, and prospective basement host rocks may be more extensive at or very near the surface than previously thought.

Examination of Chilcotin Group outcrops reveal that almost all thick (≥30 m thick) sequences occur within 0.5 – 5 km wide paleodrainage channels and commonly contain hydrovolcanic lithofacies (Andrews and Russell, 2007; Farrell et al., 2007; e.g., pillow lava, hyaloclastite breccia, pillow-breccia deltas, and associated fluvial and lacustrine sediments). The majority of these paleochannels are parallel or sub-parallel to the courses of present-day rivers, for example, the Chilcotin River (Gordee et al., 2007). Outside of paleochannels the maximum thickness of basalt observed is ≤30 m, and usually ≤10 m (see Figure 1). Tests of this proposed paleoenvironmental control on basalt thickness by geological mapping (Farrell et al., 2008; 2010), analysis of water well and exploration drill data (Andrews and Russell, 2008; Andrews et al., *subjudice*), magnetotelluric surveys (Spratt and Craven, 2009), and seismic velocity modeling (Hayward and Calvert, 2009) confirmed the hypothesis and led to identification of further buried paleochannels in areas of no exposure.

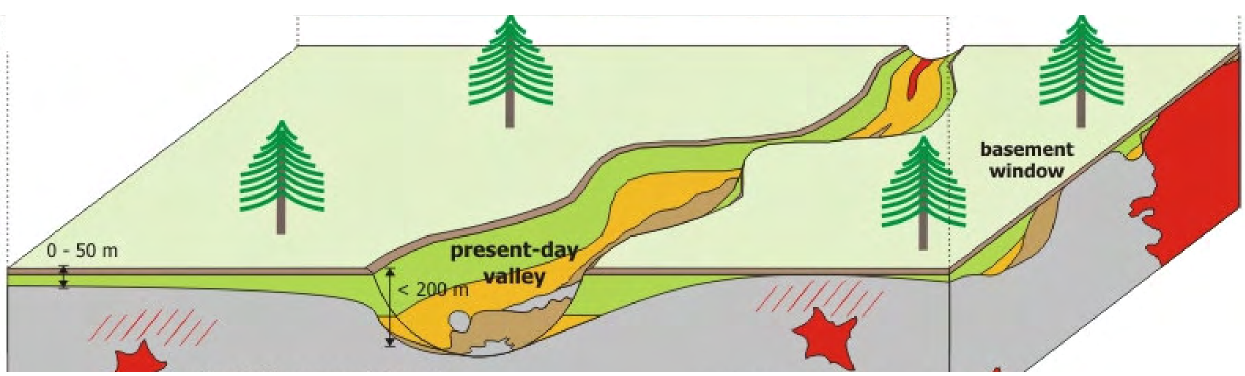

Figure 1. Schematic representation of thickness variations with the Chilcotin Group (Andrews and Russell, 2007). Basalt lavas (light green) and hydrovolcanic deposits (yellow) are thickest in paleochannels (≤200 m) and thin (0 – 30 m thick) on the adjacent plateaus.

A consequence of the relative thinness of the Chilcotin Group across much of its mapped extent is that it not contiguous (Andrews and Russell, 2007), i.e. there are many, often extensive, previously unrecognized basement windows of prospective mineral hosts (see Figure 2). The basement windows represent paleo-basement highs partly or completely surrounded by later basalt lavas. This interpretation is supported by recent geological mapping and geospatial modeling of new and archived geological, geochronological, and geophysical data (Dohaney et al., 2010a, b). We have concluded that, on average, the distribution of Chilcotin Group lavas is exaggerated by in excess of 50% on existing 1:250,000 and larger scale geological maps of the Interior Plateaus (Dohaney, 2009). This represents a considerable increase in area for new greenfields mineral exploration.

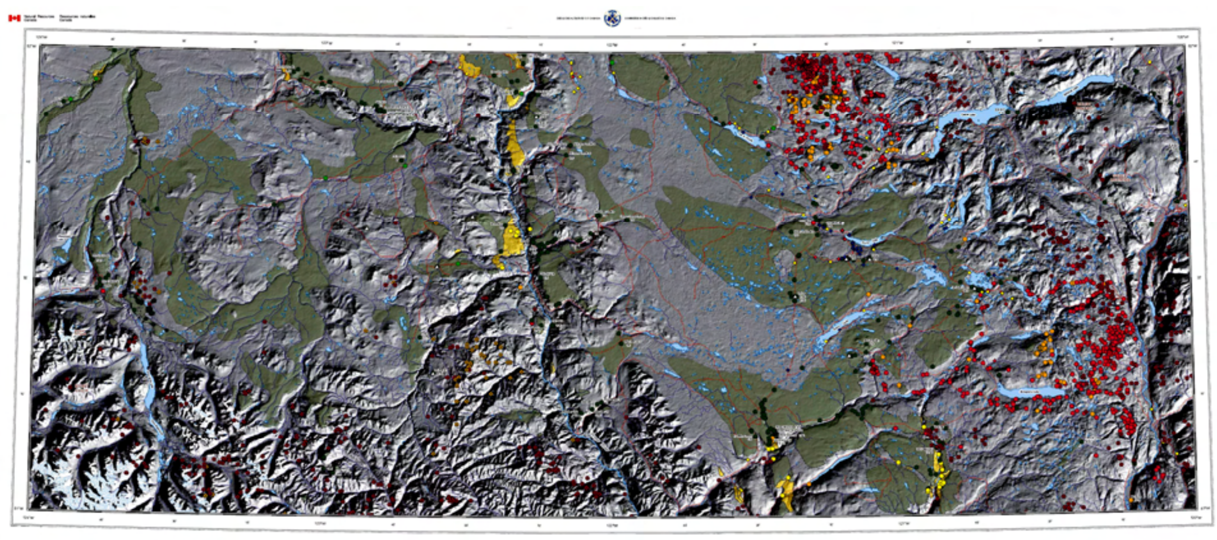

Figure 2. Revised distribution map of the Chilcotin Group (dark green) in the Taseko Lakes (092O) and Bonaparte Lake (092P) areas (Dohaney et al., 2010a), south-central British Columbia.

Geospatial modeling of water well records from the Interior Plateaus also contributes to estimating the thickness of Quaternary drift and mapping the buried bedrock surface (Andrews and Russell, 2008; Andrews et al., *subjudice*). On the physiographic plateaus, the drift is generally thin (≤10 m thick), in contrast to the deep valleys where the drift may be in excess of 200 m thick (e.g., the Fraser River valley at Prince George; Figure 2). Although this data is more scattered than desirable, our regional-scale observations support the interpretations of surficial mapping and encourage the use of techniques suited to exploration of the shallow-subsurface on the plateaus (e.g., biogeochemistry, lake and stream sediment geochemistry, till geochemistry). One unexpected bonus of this analysis has been the ability to identify buried bedrock paleochannels (e.g., Figure 3) that might host non-reworked placer Au deposits, in particular around the northern and southern margins of the Cariboo gold field.

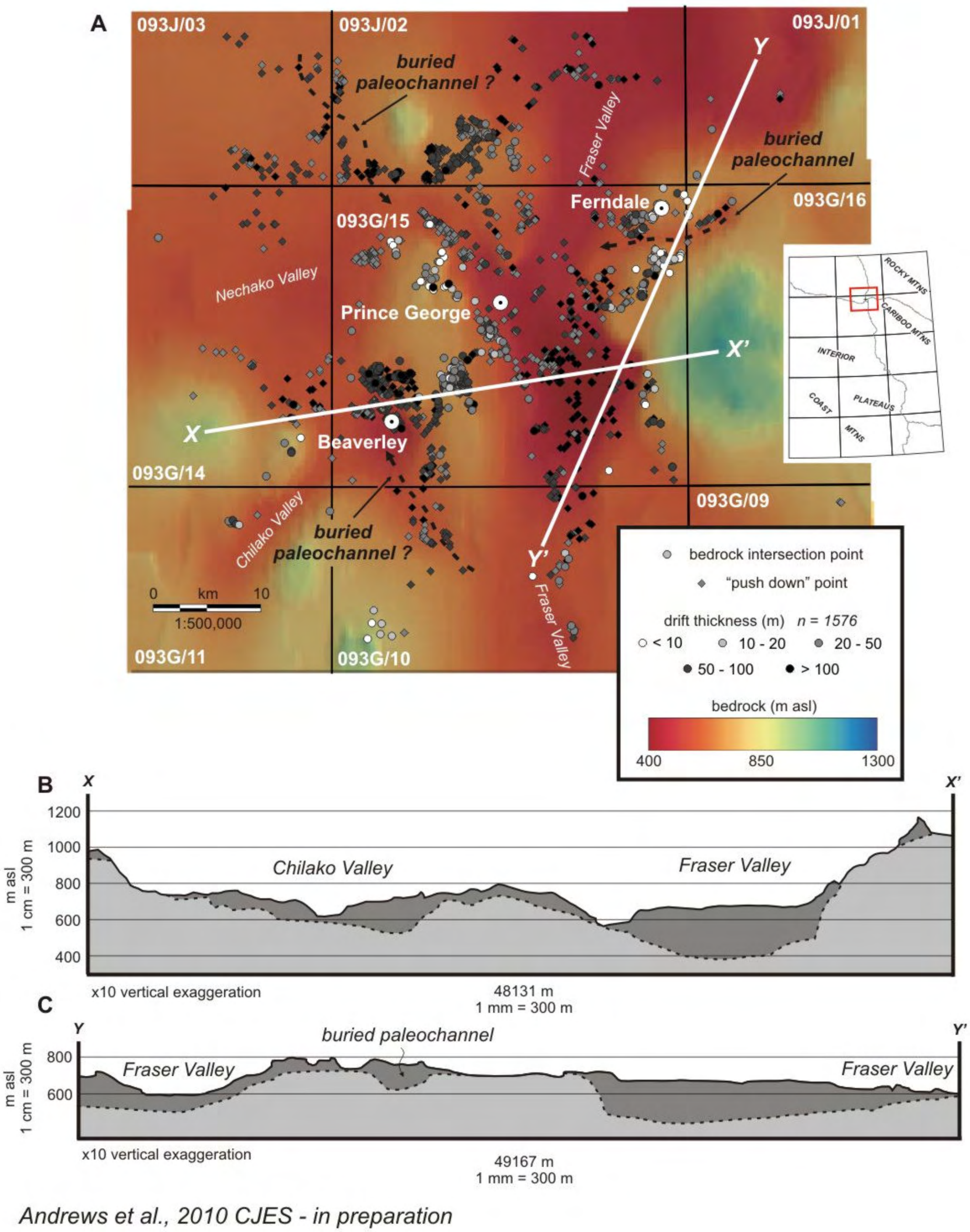

Figure 3. Bedrock elevation map (A) and schematic cross-sections (B and C) of the Prince George area (Andrews et al., *subjudice*). The drift thickness is represented by different colours of dots (wells); warmer background colours represent bedrock at lower elevations (i.e. 'deeper'). Cross-sections B and C demonstrate the thick variable thickness of drift (dark grey) over the variable bedrock relief (dashed line).

In summary, our results should encourage renewed and enhanced exploration for mineral and hydrocarbon resources on the Interior Plateaus. Reduction in the areal extent and thickness of the Chilcotin Group, combined with better constraints on the thickness of Quaternary drift, reduces the risk and expense in exploration, and the uncertainties of interpreting geophysical and geochemical surveys. These new data-sets, interpretations, and map products will enable explorationists to better target exploration programs and in combination with other geoscience projects in the area, open up extensive areas of the Plateaus for further investigation.

This research was generously supported by Targeted Geoscience Initiative 3, Geoscience BC, MITACS, and the GSC's Mountain Pine Beetle Initiative.

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ESS Contribution number 20090395

Targeting mineralized Late Triassic to Early Jurassic plutons in the Nicola Arc, southern Quesnel Terrane, Canadian Cordillera.

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In grassroots exploration for porphyry and VHMS deposits, it remains a significant challenge to target the specific mineralized host strata or plutonic phase in complex volcanic arc environments. We have successfully developed a new application for routine Pb isotopic characterization of mineralized and unmineralized Late Triassic Nicola Arc rocks in southern Quesnel Terrane of the Canadian Cordillera, known for their local, rich porphyry and minor VHMS mineral deposits.

Key to this approach is the accuracy of age, composition and distribution of magmatism. Compilation of previously-published and acquisition of eight new high-precision U-Pb (zircon) crystallization ages define at least 4 eastwardly-younging coeval and compositionally-similar plutonic suites (Figs. 1 and 2). The suites are related to the evolution of the Late Triassic to Early Jurassic Nicola Arc (Quesnel Terrane) and include: (1) Late Triassic Guichon Creek (ca. 212-208 Ma; with world class, calc-alkaline porphyry Cu-Mo±Au mineralization); (2) latest Late Triassic Copper Mountain (ca. 206-200 Ma; with significant alkaline porphyry Cu-Au±Ag-mineralization); (3) Early Jurassic Wildhorse (ca. 197-192 Ma; with local calc-alkaline porphyry Cu±Au±Mo prospects); and, (4) latest Early Jurassic Iron Lake (ca. 190-182 Ma) poorly mineralized alkaline mafic to ultramafic intrusions. The Triassic-Jurassic age progression recorded in these suites may relate to 1) shallowing of an east-dipping Cache Creek slab over time, 2) to magma generation at different depths, by different mechanisms, within the subduction zone, or 3) a combination of subduction and post-subduction melt processes as collision with the outboard Stikinian block proceeds.

The foregoing refinement of intrusive suites for the southern Quesnellian metallogenic porphryry belt provides the framework for an updated assessment of each suites' isotopic character, with an emphasis on the Pb isotopic systematics for application to exploration (Figure 3). This approach is a departure from the conventional application of Pb-isotopic analysis of K-feldspar and galena to date stratiform deposits, in that it maximizes the utility of recent advances in multi-collector inductively-coupled plasma mass-spectrometry (MC-ICP-MS). This newer analytical method enables analysis of whole-rock samples with very low abundances of Pb (<1 ppm) with significantly improved precision, compared to the thermal ionization mass-spectrometry method.

The Pb-isotopic compositions determined by MC-ICP-MS rigorously discriminate between mineralized and poorly mineralized granitic hosts (Figure 3). Late Triassic calc-alkaline Guichon (Highland Valley District), and alkaline Copper Mountain plutonic suites, with their respective porphyry Cu±Mo±Au and Cu-Au±Ag deposits are clearly distinguished from similar-aged but sparsely mineralized Early Jurassic Wildhorse Plutonic Suite batholiths, which are consistently more radiogenic (higher $^{207}Pb/^{204}Pb$) than their mineralized counterparts.

Discrimination of basaltic rocks in the Late Triassic and Early Jurassic components of the Nicola Group, whose fossil ages indicate that they are coeval with some of the intrusions, is also successful. The Pb isotopic compositions of the volcanic rocks mimic the compositional trends of the coeval plutonic suites; for example, one sample with a Pleinsbachian fossil age plots consistently in Pb isotopic space for the Early Jurassic Wildhorse intrusions.

FIGURES

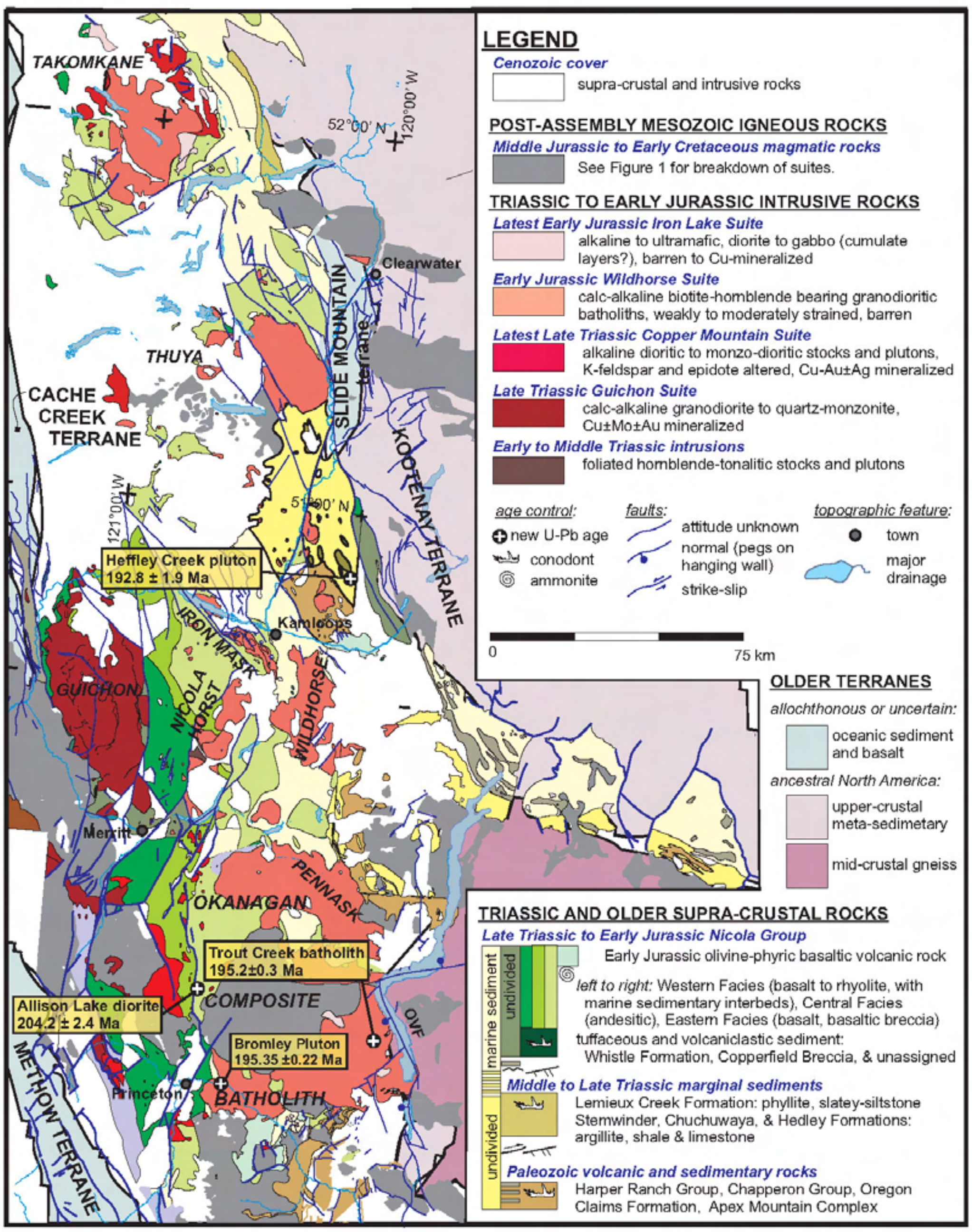

Figure 1. Plutonic suites, stratigraphic assemblages and localities for newly-dated plutons in the southern Nicola Arc.

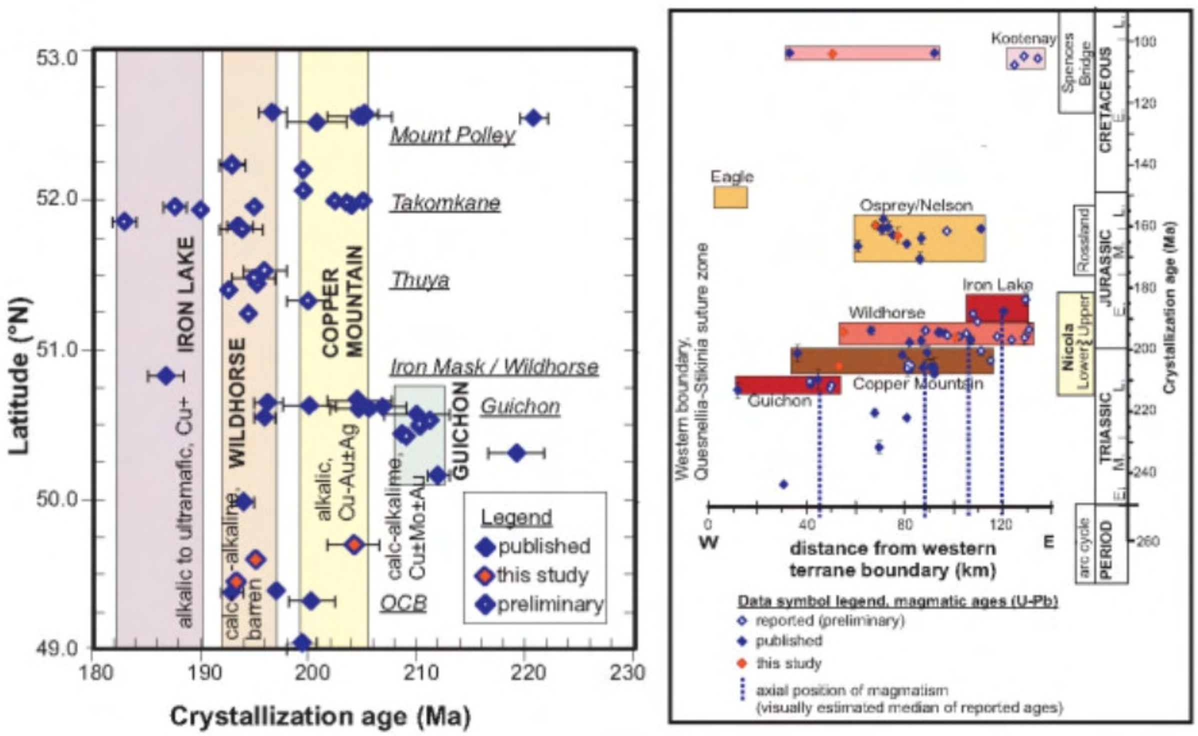

Figure 2. Time-space distribution of U-Pb dates for Late Triassic and Early Jurassic plutonic suites in southern Nicola Arc. Left plot shows U-Pb (zircon) crystallization age data used to temporally define the four suites. Right plot shows eastwardly-younging trend for the suites compared to a putative western arc edge for the southern Nicola Arc.

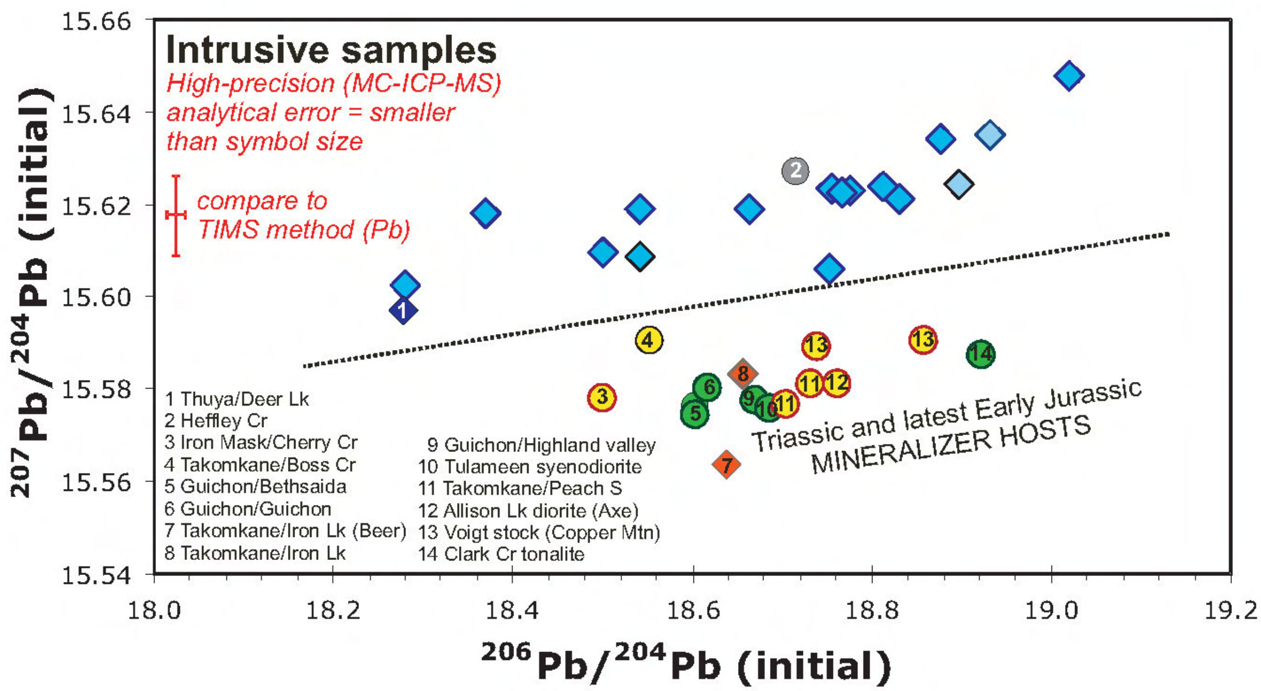

Figure 3. The Pb-isotopic compositions determined by MC-ICP-MS rigorously discriminate between mineralized and poorly mineralized granitic hosts in the Guichon (green circle), Copper Mountain (yellow circle) and Wildhorse (blue diamond) plutonic suites.

Bedrock, surficial, geophysical and geochemical mapping reveals exploration targets in the Thuya batholith, southern Nicola Arc

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The composite Late Triassic-Early Jurassic Thuya Batholith, prospective for base and precious metals, occurs in the southern Nicola Arc (Quesnel Trough) of Quesnellia, between well-known porphyry districts at Highland Valley (Cu-Mo) and Afton-Ajax (Cu-Au) to the south and Gibraltar (Cu-Mo) and Mt. Polley (Cu-Au) to the north. Limited mapping and low-precision K-Ar and U-Pb isotopic dates had suggested a correlation with the latest Triassic Guichon Creek suite, and, by inference, calc-alkaline porphyry Cu-Mo potential.

Assessing the mineral potential of the batholith is challenging due to limited exposure, and shallow burial beneath significant Tertiary volcanic and Quaternary glacial deposits. Multiple approaches are required, therefore, to evaluate the batholith's mineral potential, including: bedrock and surficial mapping; physical volcanology; high resolution geophysics; till geochemistry; and biogeochemical studies of pine and spruce.

Recent bedrock mapping and high-precision U-Pb dates (Figure 1) indicated a complex, multi-episodic intrusion of heterogeneous and homogeneous plutonic phases in the Thuya Batholith. Upper Triassic (Carnian) Nicola Group clinopyroxene-bearing volcaniclastic and sedimentary country rocks were deformed, metamorphosed and locally mineralized during intrusion (e.g., Schiarriza et al., 2002; Figure 2).

The batholith includes the latest Triassic (<202 Ma to $\geq$198 Ma) Rayfield River phase in the west, the Early Jurassic (196-193 Ma) Eakin Creek suite in the east, and medial Middle Jurassic (164-161 Ma) Bonaparte Lake phase (Figure 3). The oldest phases and suites represent members of the recently re-defined regional plutonic suites (see Breitsprecher et al., this volume) including: Copper Mountain (ca. 206-200 Ma; with significant alkaline porphyry Cu-Au-Ag-mineralization); and, Early Jurassic Wildhorse (ca. 197-192 Ma; with less-well recognized Cu-Mo+/-Au porphyry mineralization (e.g. past-producing Brenda Mine and newly discovered Woodjam SE zone in Takomkane Batholith to north).

The latest Triassic Rayfield River phase, comprising hornblende-biotite syenite, is the host for the alkaline porphyry Cu-Au gold deposit of the same name. In the Rayfield River area, north- and east-trending brittle faults localize some alteration and base-metal mineralization and apparently were remobilized to localize Neogene, basanite and nephelinite centres which contain mantle xenoliths.

The heterogeneous Early Jurassic Eakin Creek suite consists of biotite-hornblende diorite and quartz monzodiorite which grade radially inwards to quartz monzonite and alkali feldspar megacrystic monzogranite phases. Propyllitic alteration is widespread and characteristic. The mafic rocks along the northern batholithic margin and in satellitic stocks to the north are associated with many of the base metal Cu-rich showings (Fig. 4) Ultramafic and minor syenitic rocks (Dum Lake suite) and hornblendite agamatite occur mainly along the north-eastern flank of the batholith. Dum Lake suite rocks exhibit listwanite alteration and host Au vein and PGE occurrences.

The younger, higher level, unaltered, felsic and apparently unmineralized biotite monzogranite of the Middle Jurassic Bonaparte Lake phase (ca. 163-161 Ma) underlies much of the western and central areas, near Bonaparte Lake.

The composite Mt. Hagen stock along the south-eastern flank of the batholith is mainly underlain by texturally heterogeneous biotite syenite phases which intruded micro-diorite. A bladed, alkali feldspar porphyry pegmatite variant of the syenite phase hosts copper-gold showings near the summit of Mt. Hagen.

A variety of geochemical compositions and affinities are represented in the batholith. Rayfield River and Mt Hagen syenites are alike and alkaline, feldspathoid-normative, and very high-K (shoshonitic). The Early Jurassic Eakin Creek suite ranges from subalkaline to alkaline and is generally high-K; partial overlaps and changes in compositional trends for the mafic and felsic phases are typical of a fractionated suite. Middle Jurassic Bonaparte Lake phase exhibits subalkaline, calc-alkaline, and medium-K characteristics. All units are metaluminous, lack Eu anomalies in the chondrite-normalized rare earth patterns and have volcanic arc granite trace element compositional affinities.

Miocene Chilcotin Group basalt flow rocks cover the mineralized basement rocks but improved models of landscape control on lava facies distribution, and assessment of existing and new geological and geophysical survey data help minimize their well-known impediments to mineral exploration (see Dohaney et al., (2010) and Andrews et al., this volume).

High resolution aeromagnetic and radiometric maps (see Thomas and Pilkington (2008) and Thomas et al., this volume) refine distribution of host and cover volcanic and granitoid rocks which locally have a strong correlation with aeromagnetic patterns. Other derivative magnetic maps identify cryptic faults.

Surficial mapping and mineralogical and geochemical analyses of till samples (see Plouffe et al., 2009, 2010 and this volume) indicate that two glacial ice movements resulted in dispersal of gold and base metal minerals and geochemical anomalies to the west and south of their source areas.

More than 500 chemical analyses of outer bark samples from spruce and pine help discern compositionally-distinct bedrock substrate, provide focus for follow up work in areas yielding anomalous levels of metals absorbed by the trees, and possibly identify concealed mineralization (see Dunn et al., this volume).

These studies combine to suggest a focus for base and precious metal exploration along the northern and western margins of the Thuya Batholith, specifically targeting the Eakin Creek mafic phase diorite and Rayfield River and Mt. Hagen syenite phases.

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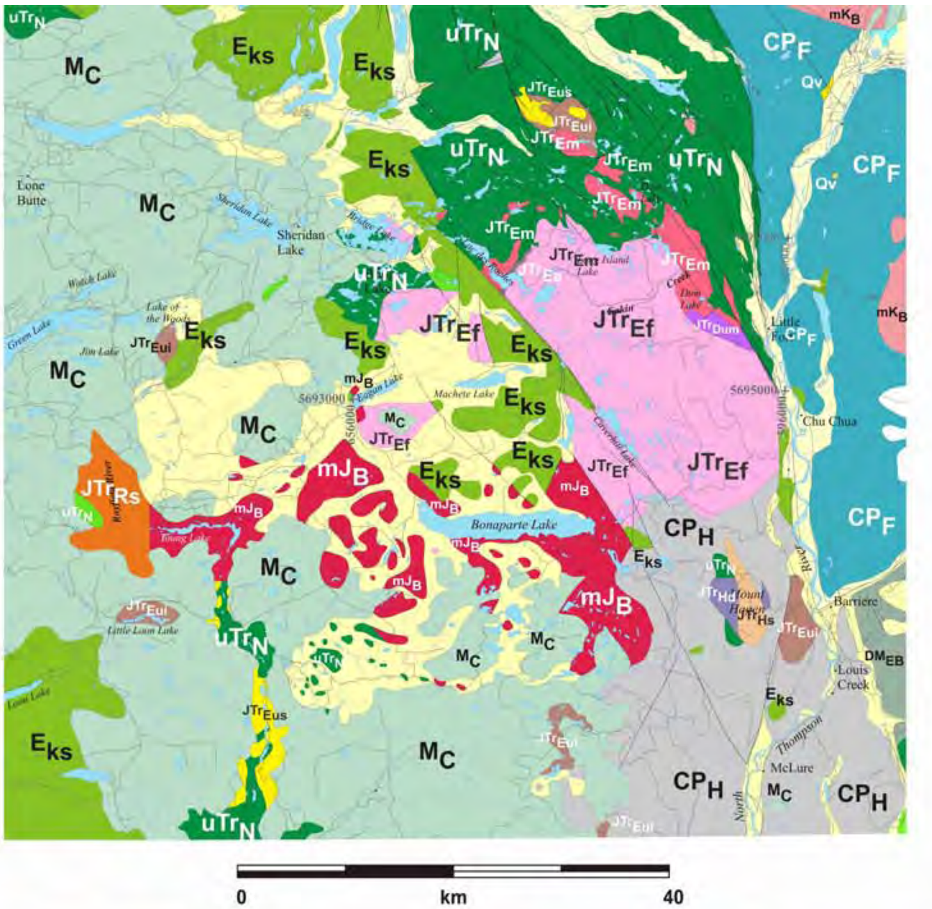

Stratified Rocks

Quaternary

Q / Qv — Pleistocene glaciofluvial and glaciolacustrine sediments; Qv: basalt flows

Neogene

M_C — **Chilcotin Group:** dark grey, vesicular, (pyroxene-) olivine basalt.

Eocene (and Oligocene?)
Kamloops Group

E_{ks} — **Skull Hill Formation:** biotite rhyolite and dacite, vesicular, plagioclase-clinopyroxene phyric basalt, andesite, and volcaniclastic rocks.

Upper Triassic and Lower Jurassic
Nicola Group

uTr_N — undivided; clinopyroxene-rich, andesitic volcaniclastic, sandstone, siltstone, minor limestone

Carboniferous--Permian
Harper Ranch Group

CP_H — undivided; rusty siltstone, argillite, chert, limestone

CP_F — **Fennell Formation:** undivided; pillowed basalt, lesser chert, slate, siltstone, gabbro and diabase

Devonian-Mississippian
Eagle Bay Assemblage

DM_{EB} — undivided; quartzite, phyllite, quartz grit, mafic volcanic rocks, limestone

Intrusive Rocks

Mid-Cretaceous
Mount Baldy suite

mK_B — biotite monzogranite; undivided

Middle Jurassic
Bonaparte Lake phase *(164-161 Ma)*

mJ_B — biotite monzogranite; fresh, apparenlty unmineralized

Early Jurassic – latest Triassic
Mount Hagen complex

JTr_{Hs} — alkali feldspar syenite; very heterogeneous, coarse-grained and leucocratic

JTr_{Hd} — diabase

Eakin Creek suite *(196-193 Ma)*

JTr_{Eus} — undivided felsic and syenitic plutonic rocks

JTr_{Eui} — undivided intermediate and mafic plutonic rocks

JTr_{Ef} — felsic plutonic rocks: quartz monzodiorite and locally megacrystic hornblende-biotite quartz monzonite and monzogranite; propyllitic alteration and accessory titanite characteristic

JTr_{Em} — mafic plutonic rocks: hornblende diorite and biotite-hornblende quartz monzodiorite; propyllitic alteration and accessory titanite characteristic

JTr_{Ea} — agmatite; coarse-grained hornblende diorite, gabbro, mafic pegmatite

JTr_{Dum} — Dum Lake ultramafite: clinopyroxenite and fine-grained diabase and basalt; local associated mineralized biotite quartz syenite

Rayfield River phase *(~202 to ≥198 Ma)*

JTr_{Rs} — hornblende alkali feldspar syenite

Figure 1. Bedrock geological map for the Thuya Batholith.

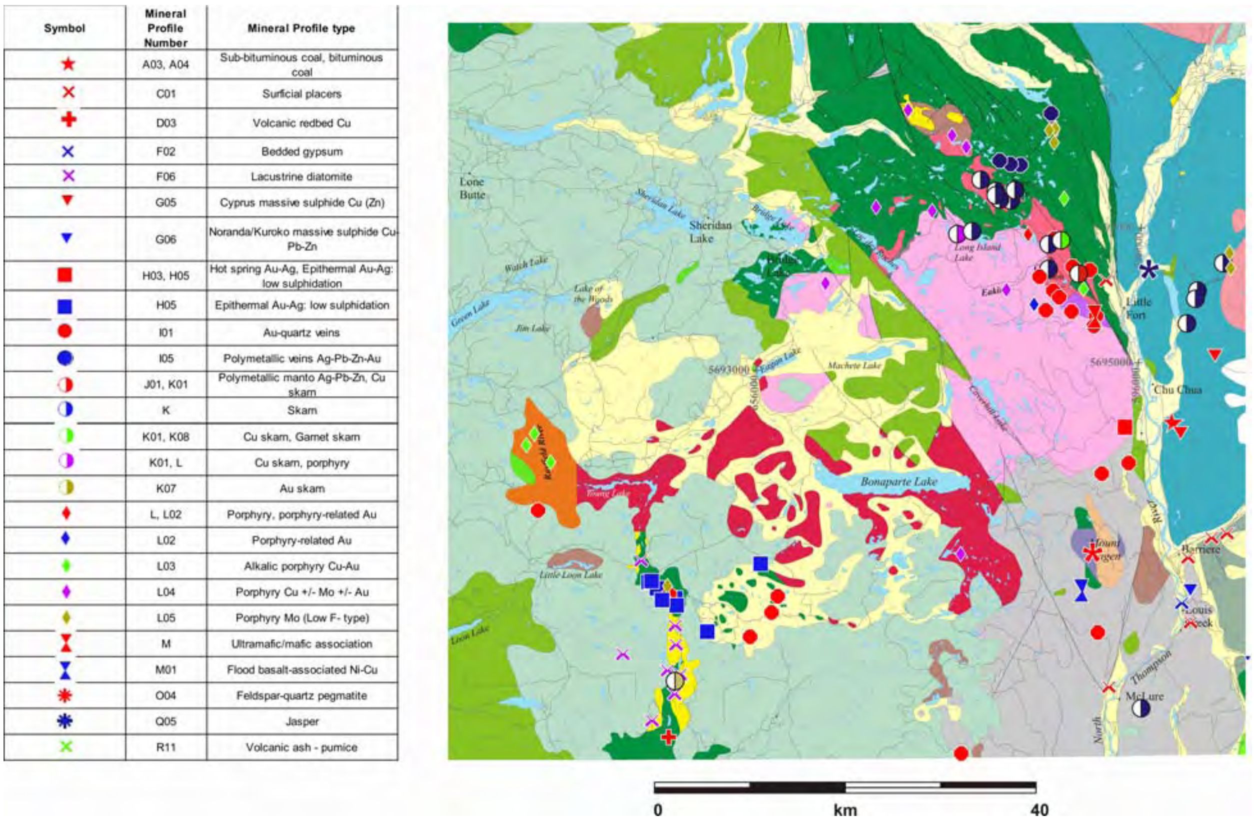

Figure 2. Mineral occurrences and mineral profile types (from BCMEMPR MINFILE) for the Thuya Batholith; unit colours the same as in Figure 1.

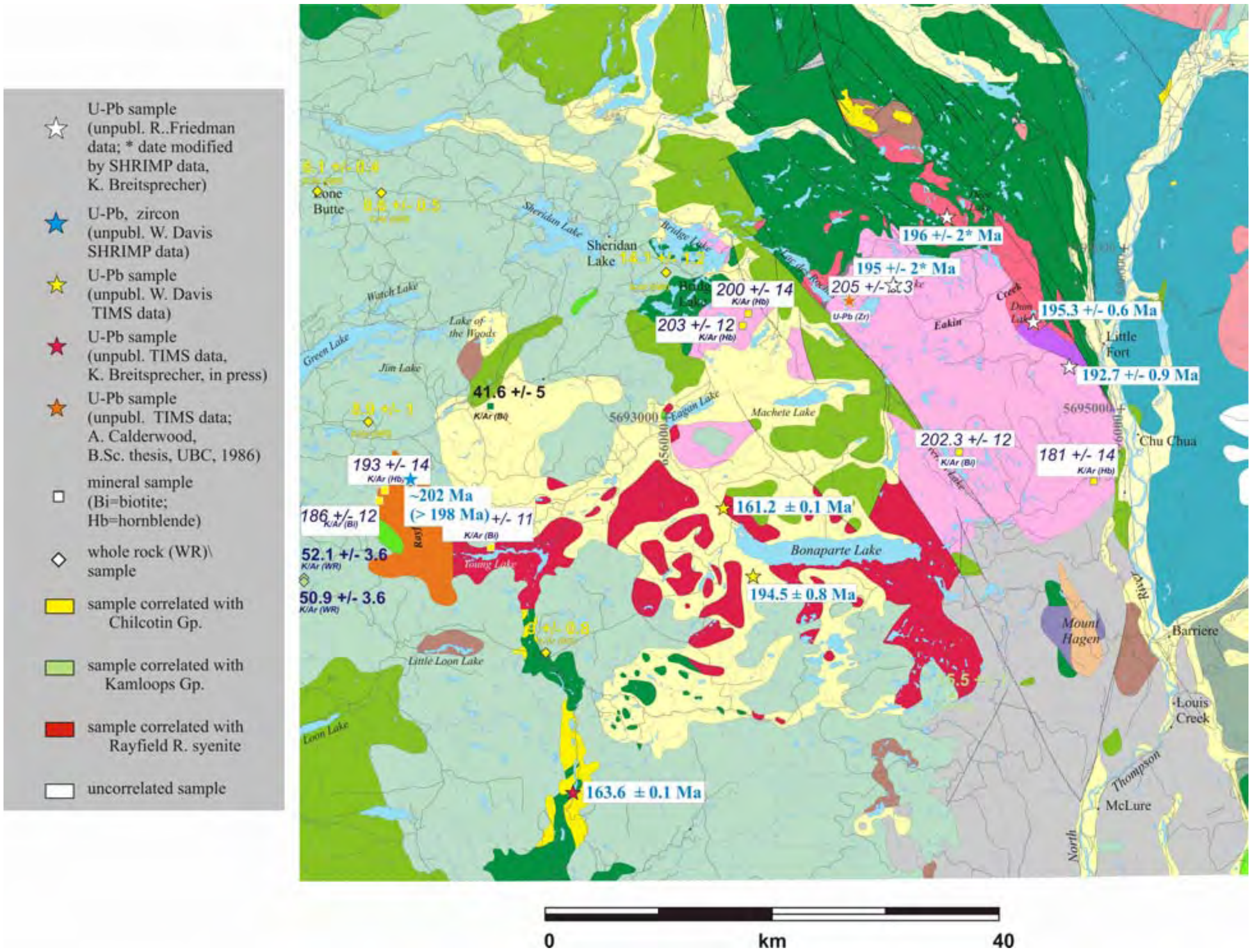

Figure 3. Published and unpublished low-precision K-Ar and high-precision U-Pb dates for the Thuya Batholith and Miocene Chilcotin Group cover rocks; unit colours the same as in Figure 1.

ESS Contribution No.

Devonian-Mississippian strata and their economic implications in the northern Kootenay Arc

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In light of new field and laboratory data, we reinterpret the age and structural-stratigraphic relations of certain Paleozoic strata exposed in the northern Kootenay Arc, with significant implications for local metallogeny. In the Selkirk mountains of southeast B.C. between the valleys of Trout and Upper Arrow lakes (Figure 1), an extensive assemblage of strata are re-interpreted as Upper Devonian and (or) Lower Mississippian in age, making them time-stratigraphic equivalents of economically important strata in the Eagle Bay assemblage and elsewhere in the Canadian Cordillera.

The strata, for which we introduce the term *Mount Sproat assemblage (MSA)*, comprise a heterogeneous package of coarse and fine grained siliciclastic and volcaniclastic metasediments with interspersed mafic to intermediate metavolcanic rocks of arc and non-arc geochemical affinities. The MSA, which was previously assigned to the lower Paleozoic Lardeau Group and the Mississippian Milford Group, occupies the limbs of a regional Jurassic syncline cored by the Middle Jurassic Kuskanax batholith. On the east limb, the MSA strikes southeastward at least 60 km from Mt. Sproat (north of Galena Bay) into the Goat Range. The west limb outcrops along Upper Arrow Lake north of Nakusp and is likely correlative with the Upper Devonian Silver Creek Formation and Bruen Phyllite of the Eagle Bay assemblage of the Shuswap Lake area. The MSA thins rapidly to the east where it onlaps the lower Paleozoic Lardeau Group. It is overlain disconformably by the metasedimentary Upper Mississippian Milford Group. We interpret the MSA to represent the eastern margin of a Devonian to Mississippian back-arc basin and thus it may be fertile ground for syngenetic sulphide exploration.

Three 1:50 000 scale maps portraying the revised geological relations are to be released as Geological Survey of Canada Open files in spring 2010.

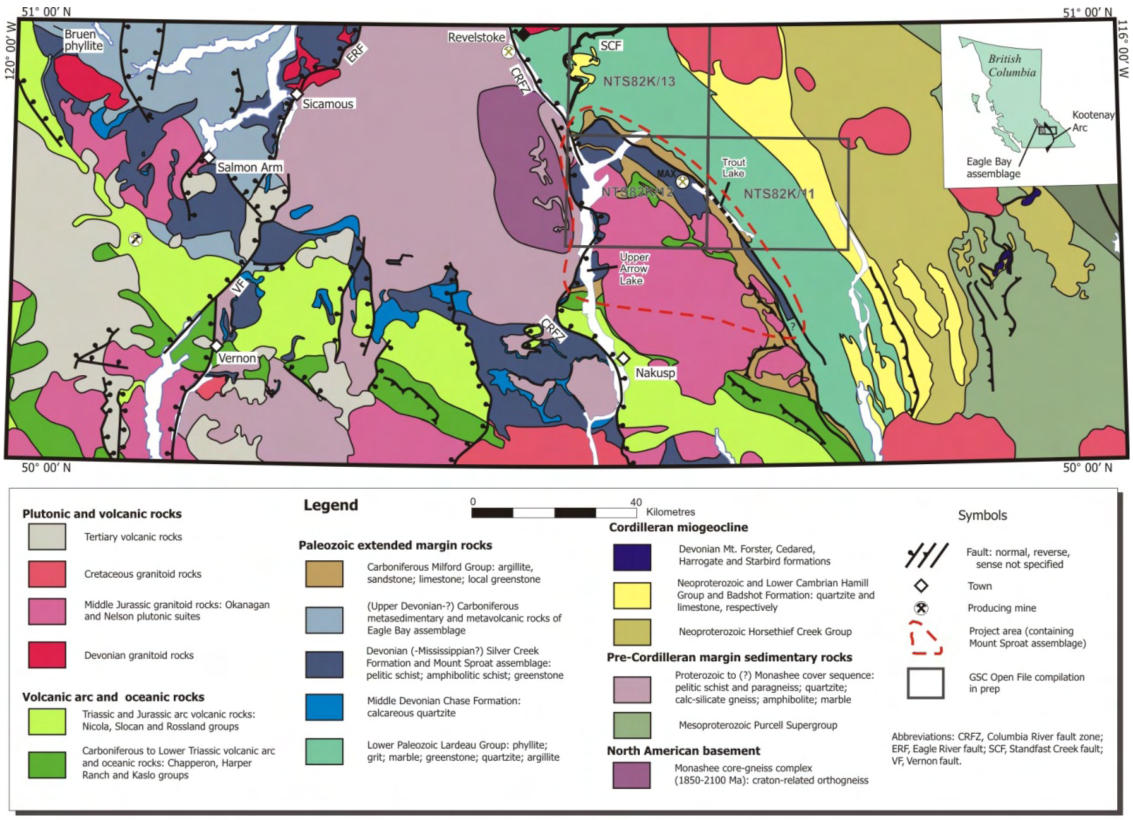

Figure 1: Geological compilation of the Vernon and Lardeau 1:25 000 scale NTS map sheets modified from Thompson et al. (2006). The project area, in which the Devonian-Mississippian Mount Sproat assemblage has been distinguished from the lower Paleozoic Lardeau Group, is outlined in red.

Carbonate-hosted sulphide and nonsulphide Pb-Zn Mineralization, British Columbia, Canada; focus on new exploration criteria

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EXTENDED ABSTRACT

The Kootenay Arc contains numerous carbonate-hosted Zn-Pb deposits (Fig. 1), including several past-producers (e.g., Reeves MacDonald, Jersey-Emerald, HB, Mastodon) and a number of advanced exploration projects (e.g., Oxide, Jackpot, Duncan, Abbott, Wigwam). The largest deposits range in size from 6 to 10 Mt and contained on average 3-4% Zn, 1-2% Pb, 0.4% Cd, and traces of Ag. The deposits are hosted by deformed and metamorphosed Lower Cambrian platformal carbonates of the Badshot Formation, or its equivalent, the Reeves member of the Laib Formation.

The present distribution and form of the deposits are controlled by the regional structure. They are essentially stratabound, lenticular concentrations of sulphides (sphalerite, galena, pyrite, local pyrrhotite and rare arsenopyrite) confined to dolomitic and/or siliceous zones, which are folded isoclinally (Fig. 2). These structures mimic the large-scale regional structures, and are commonly elongated parallel to the regional structural grain. As well, the sulphides and their dolomitic envelopes have been affected by regional and local contact metamorphism. Field and microscopic observations indicate that the sulphides appear to have formed primarily by replacement of the host carbonates, with minor open space filling of breccia zones, fractures and vugs.

The near-surface portions of several carbonate-hosted sulphide deposits are weathered, strongly oxidized, and consist of extensive Zn- and Pb-bearing iron oxide gossans and base metal-bearing nonsulphide mineralization (Fig. 3). The Reeves MacDonald, Jersey-Emerald, HB, Lomond, and Oxide group of deposits exhibit the best examples of carbonate-hosted nonsulphide base metal mineralization in the southern Kootenay Arc. Sulphide oxidation post-dates Middle Jurassic deformation (i.e., age of regional metamorphism and first phase of deformation) and may have started before or slightly after the last glacial maximum (17 000–14 000 BP). The relatively warm and dry climate, which prevailed some 10 000–7000 BP, may have been particularly favourable for supergene oxidation of sulphides and formation of carbonate-hosted nonsulphide base metal mineralization in the southern Kootenay Arc (Simandl and Paradis, 2009). However, the recent documentation of nonsulphide Pb-Zn mineralization north of the study area (Paradis et al., 2010) suggests that, under favorable geological conditions, this type of mineralization should be expected in the northern portion of the Kootenay Arc as well.

The origin of the sulphide deposits of the Kootenay Arc is enigmatic because of the intense deformation that has modified most of their original features. However, Re/Os isotope analyses on the Reeves MacDonald sulphides indicate that the mineralization occurred during the Devonian period and that the deposits are epigenetic [i.e., Mississippi Valley-type (MVT)]. They share many characteristics with other Cordilleran MVT deposits including: (1) they are hosted by altered dolomitized and/or silicified carbonates; (2) the deposits contain simple mineral assemblage of pyrite, sphalerite, and galena; (3) the mineralization is zinc-rich (high sphalerite/galena ratios: Zn:Pb from 10:1 to 2:1); (4) they display complex ore textures and alteration assemblages; (5) pyrite, sphalerite, and galena grains have isotopically heavy sulfur ($\delta^{34}S$ values = 9.0 to 26.4 per mil); and (6) galena and sphalerite have radiogenic Pb.

The new Devonian age confirms the epigenetic nature (as opposed to syngenetic) of the sulphide deposits, and improves our understanding of the genesis of these deposits in the context of the Cordilleran tectonics. The Devonian was an important metallogenic epoch that saw the proliferation of base metal deposits along the continental margin of North America with coeval development of volcanic-hosted massive sulphide (VHMS) deposits in arcs and back-arcs of the pericratonic terranes, sedimentary exhalative (SEDEX) deposits in continent-margin basins, and finally MVT deposits in continental platforms. From the prospecting point of view, determination of the physical properties of the sulphide and nonsulphide mineralization and their host rocks in the Kootenay Arc is one of the essential steps that will lead to improved interpretation of existing and future geophysical surveys. The use of portable XRF in exploration for white Zn-rich nonsulphide deposits appears as one of very promising and potentially cost-effective exploration tools.

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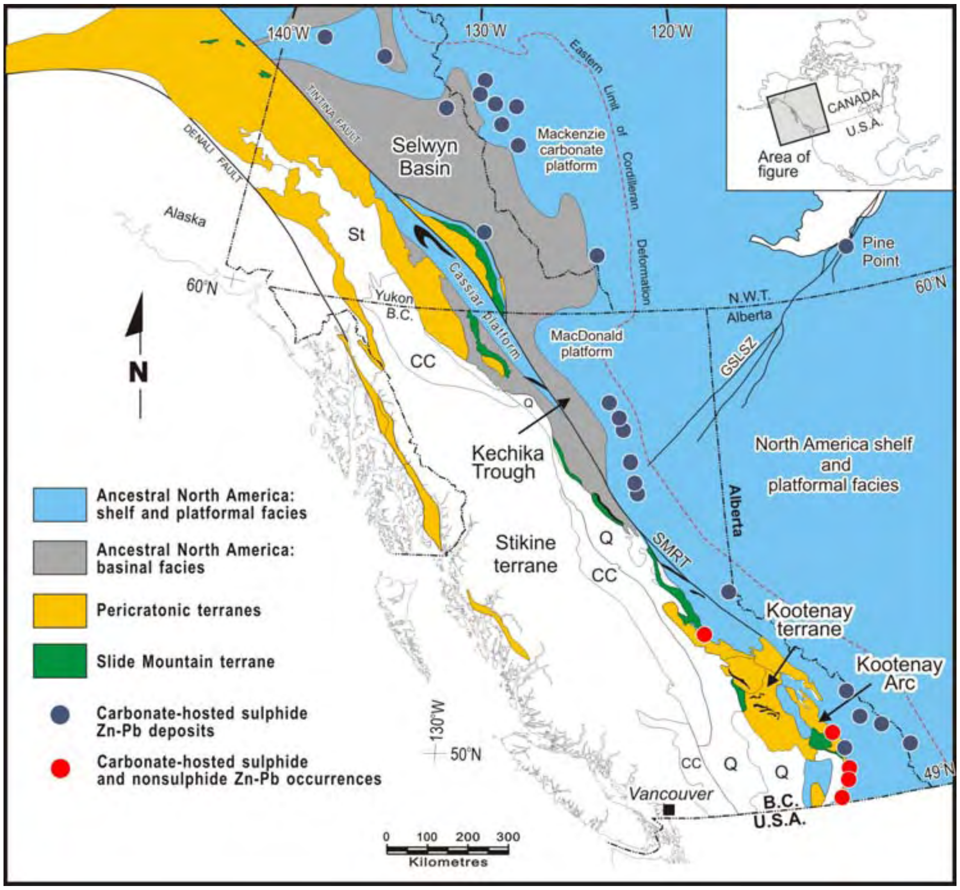

Figure 1. Location of carbonate-hosted sulphide and nonsulphide Zn-Pb deposits in the Kootenay Arc with respect to other significant carbonate-hosted sulphide and nonsulphide occurrences of the Cordillera (modified from Nelson et al., 2002, 2006). Abbreviations: St, Stikine terrane; CC, Cache Creek terrane; Q, Quesnel terrane; SMRT, southern Rocky Mountain Trench, GSLSZ, Great Slave Lake Shear Zone.

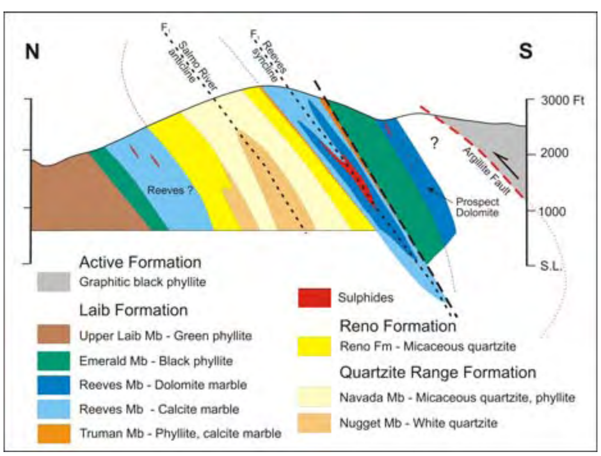

Figure 2. North-south cross–section (subnormal to major F_1 fold axes, which strike on average 230°/35-50°S) of the Reeves MacDonald deposit area (from MacDonald, 1973).

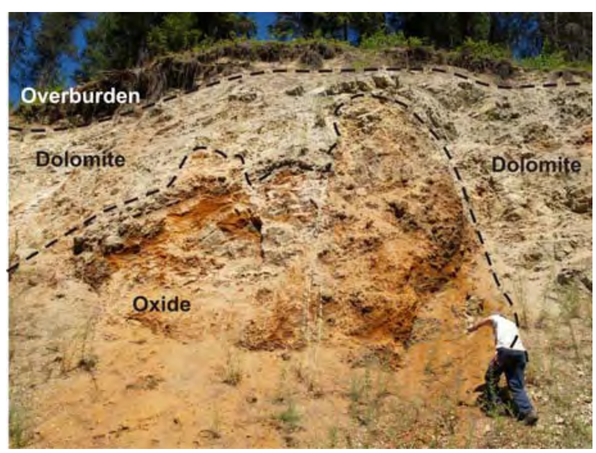

Figure 3. The main exposure at the Lomond occurrence; an example of carbonate-hosted nonsulphide base-metal deposit (gossan component); from Simandl and Paradis (2009).

Halogen analyses of fluid inclusions in the Kokanee Range Ag-Pb-Zn veins

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Introduction

Metamorphic fluids are a major component of the hydrothermal systems that form Ag-Pb-Zn veins (Beaudoin and Sangster, 1992). One characteristic of some metamorphic fluids is that they can be saline and, therefore, can transport significant amounts of base and precious metals in solution. Previous fluid inclusion studies on the Kokanee Ag-Pb-Zn veins have shown that mineralization formed by mixing of a metamorphic fluid, with salinities up to 18 wt %, with meteoric water (Beaudoin et al., 1992). The source of chloride in the metamorphic fluid, however, is unknown. The aim of this study, therefore, was to analyse the elemental halogen and chlorine isotopic composition of fluid inclusion leachates from the mineralized veins to determine the source of salinity in the hydrothermal fluids. This abstract will focus on the results in terms of the Br/Cl molar and chlorine isotope data.

Geological background and nature of the samples

The Kokanee Range vein-field, which covers an area of 2500 km^2 in southeastern British Columbia, Canada, comprises about 400 Ag-Pb-Zn veins. The vein field is a segment of the upper lithosphere that has been fractured and pervasively infiltrated by hydrothermal fluids during Eocene crustal extension of the Canadian Cordillera. Crustal extension was accommodated by displacement along the Slocan Lake fault, a low-angle, east-dipping extensional fault that has been shown, by seismic refraction, to extend across the continental crust to the Moho. The vein field is confined to the hanging wall of the Slocan Lake fault, and no Ag-Pb-Zn veins have been found in the footwall Valhalla metamorphic core complex. The veins are in northeast- and east-trending subvertical shear zones. A major east-trending fault zone, with a 35°S dip, hosts several of the larger deposits of the vein field. In general, the paragenetic sequence starts with siderite, sphalerite, galena and minor quartz, during a stage dominanted by the saline metamorphic fluid, evolving gradually to quartz-sphalerite-galena veins with late dolomite and calcite, with progressive admixture of meteoric water (Beaudoin et al., 1992). Fluid inclusions in sphalerite and quartz comprise NaCl-H_2O±CO_2 with salinities ranging from 1 to 18 wt% NaCl eq and homogenization temperatures ranging from 75 to 330 ºC. Episodic boiling has been documented in some inclusions assemblages.

A total of 54 samples of siderite, galena, sphalerite and quartz were prepared from 22 deposits that provide a regional coverage of the Kokanee Range. were analysed from locations hosted in the Middle Jurassic Nelson Batholith (Entreprise, Mountain Con, Galena Farm) and the Upper Triassic Slocan Group (Bosun, Payne, Alamo, Lucky Jim, Noble Five, Caledonia, Wonderful, Silvana, Silversmith, Richmond-Eureka, Noonday, Mammoth, Van Roi, Utica, Cork-Province, Wintrip, Gibson, and Standard).

Analytical technique

Mineral separates of galena, sphalerite, siderite and quartz were handpicked and cleaned. The samples were crushed in an agate mortar and pestle and then leached by ultraclean water. The leachate was filtered and analysed for F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-} and SO_4^{2-} by ion chromatography using a Dionex DX600. Most samples yielded data for F, Cl and SO4, but only 15 samples had Br data above the detection limit (0.008 ppm). Samples that yielded over 100ppm Cl in total were then analysed for chlorine isotopes using the technique described by Long et al. (1993) and Wassenaar and Koehler (2004). The precision on these analyses was 0.2‰.

Results:

The full dataset is presented in Table 1. The Br/Cl molar data ranges from 0.14 to 25.35*10^{-3}. There is no systematic variation in terms of the host mineral or the spatial location of the samples. Eleven samples yielded leachates with enough Cl for the chlorine isotopic study. Samples from Payne have δ^{37}Cl values that range from 0.1 to 0.21‰. Noonday and Mountain Con each yielded one δ^{37}Cl value datum of 0.33‰ and -0.47‰ respectively. The data from Entreprise range from 0.07 to 0.10 and those from Standard range from -0.07 to -0.22‰.

Table 1: Fluid inclusion anion and Cl isotopic data for the Kokanee Ag-Zn-Pb veins

Deposits	Mineral	Sample No.	F (ppm)	Cl (ppm)	Br (ppm)	SO4 (ppm)	δ^{37}Cl ‰	Br/Cl molar
Bosun	Sph	3-5sp	0.06	4.36	0.008	<0.008		
Payne	Qtz	K6-3q	<0.008	18.96	0.02	6.74	0.10	0.47
Payne	Sid	K6-3sd	0.28	31.82	0.07	64.45	0.16	0.93
Payne	Sph	K6-3sp	<0.008	10.53	<0.008	458.89		
Payne	Qtz	K6-7q	<0.008	34.88	<0.008	<0.008	0.21	
Payne	Sid	K6-7sd	0.10	10.15	<0.008	12.42		
Alamo	Qtz	8-1q	<0.008	10.83	<0.008	0.8		
Alamo	Sph	8-1sp	0.09	44.7	<0.008	786.36		
Lucky Jim	Sid	23-1sd	0.01	13.22	<0.008	500.75		
Noble Five	Sid	37-4sd	0.10	1.75	<0.008	80.20		
Noble Five	Sph	37-4sp	0.07	5.17	<0.008	161.33		
Caledonia	Qtz	41-6q	0.05	12.67	0.02	30.38		0.70
Caledonia	Sid	41-6sd	0.01	1.64	<0.008	5.34		
Wonderful	Qtz	W43-1q	<0.008	5.76	<0.008	1.31		
Wonderful	Sid	W43-1sd	<0.008	0.82	<0.008	1.21		
Silvana	Sid	50-11sd	0.03	13.13	<0.008	118.58		
Silvana	Sph	50-11sp	0.05	1.51	<0.008	531.48		
Silvana	Sid	50-12sd	0.02	3.38	<0.008	25.72		
Silvana	Sid	50-40sd	0.03	<0.008	<0.008	96.88		
Silvana	Sph	50-40sp	0.01	2.15	<0.008	313.65		
Silvana	Sid	50-44sd	0.20	4.40	0.04	18.58		3.80
Silvana	Sph	50-44sp	0.02	2.89	<0.008	78.72		
Silvana	Sid	50-49sd	<0.008	0.19	<0.008	28.96		
Silvana	Sid	50-52sd	1.47	1.77	<0.008	16.64		
Silversmith	Qtz	53-2q	0.01	5.68	<0.008	1.89		
Silversmith	Sid	53-2sd	0.06	2.66	<0.008	1068.20		
Silversmith	Sph	53-2sp	0.06	2.85	<0.008	867.03		
Richmond-Eureka	Sid	54-1sd	0.03	10.37	<0.008	42.08		
Richmond-Eureka	Sph	54-1sp	<0.008	50.90	0.14	17.02		1.22
Noonday	Sid	56-1sd	0.00	46.68	0.01	21.79	0.33	0.14
Mammoth	Qtz	60-1q	<0.008	10.28	<0.008	13.85		
Mammoth	Sid	60-1sd	0.06	8.87	<0.008	26.23		
Mammoth	Sph	60-1sp	0.01	16.76	<0.008	421.32		
Van Roi	Sph	64-3sp	<0.008	4.72	<0.008	5.99		
Galena-Farm	Qtz	67-3q	<0.008	6.01	<0.008	10.50		
Galena-Farm	Sph	67-3sp	2.44	1.46	<0.008	138.46		
Mountain Con	Qtz	81-1q	0.02	18.68	0.03	1.78	-0.47	0.71

Deposits	Mineral	Sample No.	F (ppm)	Cl (ppm)	Br (ppm)	SO4 (ppm)	$\delta^{37}Cl$ ‰	Br/Cl molar
Mountain Con	Sid	81-1sd	0.06	4.36	<0.008	5.81		
Utica	Gal	86-1g	0.06	14.52	<0.008	<0.008		
Cork-Province	Sid	94-1sd	0.10	14.97	0.03	161.11		0.80
Wintrip	Qtz	97-2q	0.09	12.41	0.01	4.26		0.36
Wintrip	Sph	97-2sp	<0.008	5.88	0.34	<0.008		25.35
Gibson	Gal	121-10g	<0.008	2.86	<0.008	134.09		
Gibson	Sid	121-10sd	0.01	5.29	<0.008	82.30		
Gibson	Sph	121-10sp	<0.008	6.72	<0.008	212.81		
Entreprise	Qtz	148-1q	0.03	12.71	0.16	23.86		5.60
Entreprise	Sid	148-1sd	0.20	19.46	0.45	8.08	0.10	10.21
Entreprise	Qtz	148-9q	<0.008	23.98	0.03	0.89	0.09	0.56
Entreprise	Sid	148-9sd	0.10	25.73	0.12	36.98	0.07	2.01
Entreprise	Sph	148-9sp	0.01	5.61	<0.008	105.31		
Standard	Gal	180-5g	0.01	27.51	<0.008	176.68	-0.07	
Standard	Qtz	180-5q	<0.008	11.23	<0.008	3.6		
Standard	Sid	180-5sd	0.01	22.76	0.01	9.44	-0.22	0.19
Standard	Sph	180-5sp	0.07	72.15	0.04	762.05	-0.08	0.27

sph = sphalerite; sid=siderite; qtz=quartz; ga=galena

<u>Discussion:</u>

The Br/Cl molar ratio data have values that are both higher and lower than the present day seawater value of $1.52*10^{-3}$, which overlaps the mantle value of 1 to $2*10^{-3}$. Some samples have Br/Cl molar ratios significantly higher than the mantle or seawater values. The source for these unusually Br-rich samples is unknown but the most likely explanation is that there may be an organic source of Br contributing to a small number of samples in the system (e.g. Worden 2002). This material may be derived from the black shales of the Slocan Group.

There are two potential sources of salinity in fluids with Br/Cl molar ratios less than the seawater value. One is a fluid which has acquired its salinity by the dissolution of halite, which typically has low Br contents. The second potential source is a magmatic fluid such as those found in porphyry deposits. Although many of the data have values lower than mantle Br/Cl values, there are some rare data from porphyry deposits with magmatic hydrothermal fluids with values less than this (e.g. Bingham Canyon with ratios as low as 0.18; Nahnybida et al., 2009). So, although less likely, a magmatic source for the fluid cannot be wholly rule out in terms of the elemental data.

The $\delta^{37}Cl$ composition of the mantle is not well constrained at this time but appears to range from 0‰ to more negative values (see Gleeson & Smith 2009 for discussion). The composition of the crust is thought to be dominated by the isotopic composition of seawater and evaporites with values of 0±0.5‰ (Eastoe et al., 2002). The $\delta^{37}Cl$ data from Bingham Canyon, corresponding to the low Br/Cl molar ratios is highly negative. Therefore, the Kokannee $\delta^{37}Cl$ data documented here is more compatible with a halite dissolution source for the salinity in these fluids. This does not preclude a deep-seated metamorphic source of the fluids as suggested by Beaudoin et al. (1992). Although there is not currently a thorough understanding of the halogen behavior during metamorphism, studies suggest that metamorphic fluids can retain their original halogen compositions through the metamorphic cycle as long as significant amounts of Cl-bearing mineral phases are not formed (Yardley & Graham 2002). The total salinity of the fluids may increase by dehydration reactions but this should not affect the Cl/Br ratio. In this case, the mineralizing fluids could either have acquired their chlorinity prior to metamorphism by halite dissolution or during metamorphism by the breakdown of Cl bearing minerals that had a previously acquired halite dissolution signature.

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Basinal dewatering via the basement: evidence for infiltration of Paleozoic basinal brines into Mesoproterozoic rocks of the Purcell anticlinorium, southeastern British Columbia.

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The Mesoproterozoic Belt-Purcell basin of southeastern British Columbia and northwestern U.S.A. has an unusually high metal endowment. The value of production and measured resources based on inflation-adjusted 10 year metal prices is about $141 billion. This wealth is supplied by a range of mineral deposit types that have been attributed to either Jurassic-Cretaceous or Mesoproterozoic metallogenetic events. The major producer of the Belt-Purcell basin in Canada has been the Sullivan deposit, a Sedex deposit which produced Zn-Pb-Ag ores worth nearly $30 billion. Sullivan is hosted by the turbidite-mafic sill complex of the Aldridge Formation which forms the lower part of the 18 km thick Purcell Supergroup. Like other Sedex deposits (e.g. Lydon, 1996), Sullivan is spatially associated with synsedimentary faulting, but, unlike most other Sedex deposits, it formed during the rift phase, instead of the more typical sag phase, of a sedimented rift system. Studies aimed at understanding the tectonics and metallogeny of the sag phase of the upper part of the Purcell Supergroup reveal that the migration of fluids through rock of the Belt-Purcell basin during the Paleozoic may also have contributed to the metal inventory of the basin.

The sag phase of the Belt-Purcell rift is marked by a decrease in accumulation rates of strata above the Nicol Creek Formation (Lydon, 2000). These sag phase strata are collectively referred to as the Dutch Creek Formation (Walker, 1926). On the eastern limb of the Purcell anticlinorium (Fig. 1) the Dutch Creek Formation is divided into the Sheppard, Gateway, Phillips and Roosville formations, and is conformably overlain by the Mount Nelson Formation (Höy, 1993) (see Legend Fig. 1 and Fig. 2). Abrupt changes in thickness of lithological units between the Northern Hughes Range and the Purcell Mountains are explained by a series of synsedimentary faults (Höy, 1993; Gardner, 2008) that cumulatively accommodate a westward increase of about 2.5 km of post-Aldridge and pre-Mount Nelson strata (Fig. 2). Synsedimentary faulting is corroborated by the stratigraphic displacement of the boundary between diagenetic pyrrhotite and diagenetic pyrite, which occurs in the lower part of the Middle Aldridge Formation in the Hughes Range and the Creston Formation in the Purcell Mountains, and is interpreted to represent a hydrologic boundary between pore fluids of contrasting density and composition (i.e. a horizontal datum at the time of burial diagenesis) (Fig. 2).

New detrital zircon data from the western limb of the Purcell anticlinorium indicate that clastic rocks immediately below the Mount Nelson Formation were derived from a western continent, typical of pre-Dutch Creek Formation equivalents (Missoula Group) of the western part of the Belt-Purcell basin in the U.S.A. (Ross and Villeneuve, 2003). Missing on the western limb of the Purcell anticlinorium in Canada are rocks containing detrital zircons of syn-Belt-Purcell age in the 1445-1380 Ma range, typical of the Dutch Creek Formation on the eastern limb (Gardner, 2008). The apparent absence of the Dutch Creek Formation suggests a substantial hiatus below the Mount Nelson Formation on the western limb of the Purcell anticlinorium, which in turn implies a synsedimentary fault system with up to 4 km of east side down vertical movement to explain the erosion and/or non-deposition of post-Creston and pre-Mount Nelson strata (Fig. 2). The locus of this fault system is suggested to be in the north trending Redding Creek fault – Hall Lake fault corridor (Fig. 1).

The only deposits of possible Sedex affinities that have been mapped as being in the rift sag sequence are close to this suggested fault system. These are highly deformed Zn-Pb±Ba deposits in carbonate rocks on the western limb of the Purcell anticlinorium. Lead isotopes of galena from these deposits lie on a line joining the field of Mesoproterozoic Zn-Pb deposits of the Belt-Purcell basin and a field of Zn-Pb±Ba deposits that are hosted in carbonate rocks as young as Cambrian elsewhere in southeastern British Columbia (Fig. 3). This suggests an involvement of Paleozoic fluids that formed or modified the mineral deposits in Mesoproterozoic and Neoproterozoic host rocks. All these deposits occur within a narrow, linear, north-south corridor nearly 200 km long that extends from near Creston to the Kicking Horse Pass in the Rocky Mountains forming a northward continuation to the trend of the suggested fault system (Fig. 4). This trend approximately coincides with the western margin of the Windermere High that controlled the margins of sedimentary basins during the lower Paleozoic. The longevity of this structural trend from its origins in the Mesoproterozoic via its control on sedimentary basins during the Paleozoic to its localization of faults during Laramide thrusting, suggests that it reflects a structure in the Paleoproterozoic/Archean basement.

The Sullivan-North Star Corridor (Fig. 1) is also a north trending structure which controlled the upflow of hydrothermal fluids that formed the Sullivan deposit. Late alteration in the core of the Sullivan deposit produced a pyrite-carbonate assemblage in which galena is more radiogenic than the bulk of the ore galena. Beaudoin (1995) suggested that this radiogenic "Sullivan alteration" was formed up to 108my after the main ore event by hydrothermal fluids associated with the ~1370 Ma East Kootenay metamorphic event. New Sm/Nd isotope analysis of the carbonate in the alteration assemblage gives an age of 470±20 Ma (mid Ordovician). High Sm/Nd ratios of the carbonates suggest that the fluids involved were deep (post-illitization) pore fluids of a sedimentary basin (Mack and Awwiller, 1990), likely the lower Paleozoic sedimentary basins on either side of the Windermere High.

These two lines of evidence suggest that dewatering of lower Paleozoic sedimentary basins in southeastern British Columbia was, at least in part, via the basement, and utilized structures that originated as extensional faults in the Mesoproterozoic. The recognition that basin dewatering may commonly take place via its basement not only presents new exploration targets in the Purcell anticlinorium but adds a dimension to general genetic models for mineral deposits associated with sedimentary basins.

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Figures

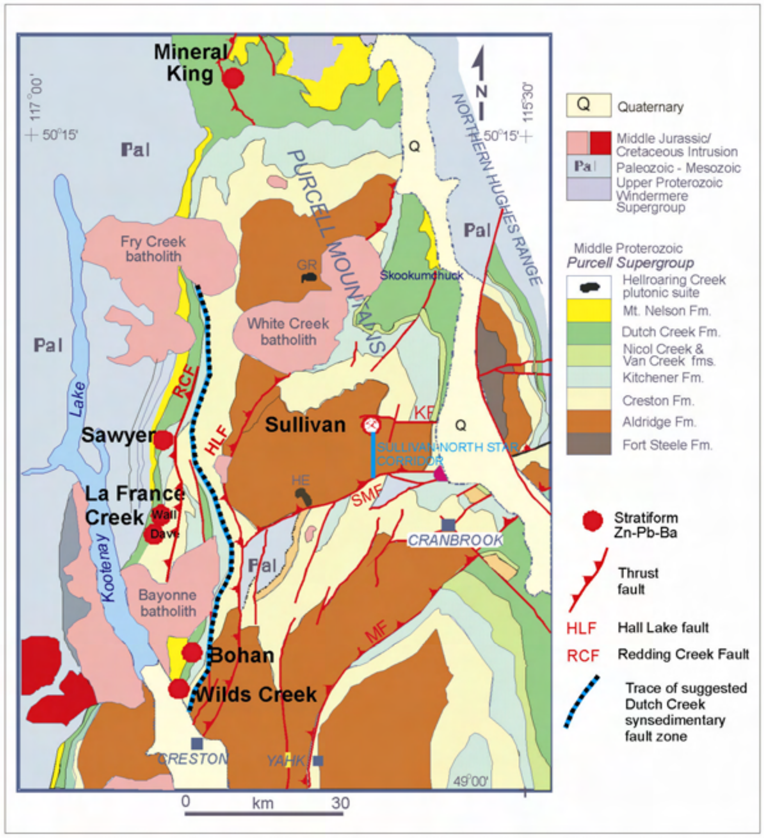

Fig. 1. Geological Map of the Purcell Anticlinorium showing locations and geological features mentioned in text. Simplified after Höy et al., 1995.

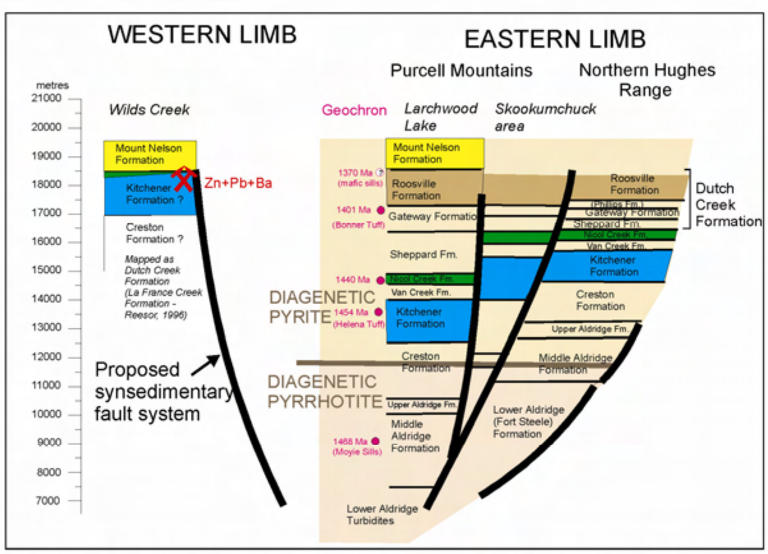

Fig. 2. Schematic section across the Purcell anticlinorium showing variations in thickness of stratigraphic units, displacements on synsedimentary faults, and stratigraphic level of the transition upwards from diagenetic pyrrhotite to diagenetic pyrite.

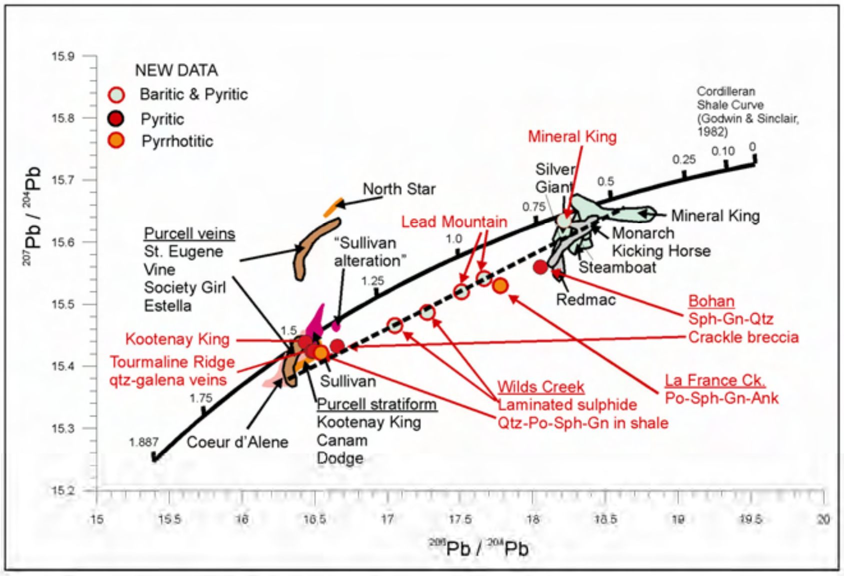

Fig. 3 Pb isotope ratios of major Zn-Pb deposits of the Purcell anticlinorium and adjacent areas. Circles represent new data. Other data shown as fields are from the literature.

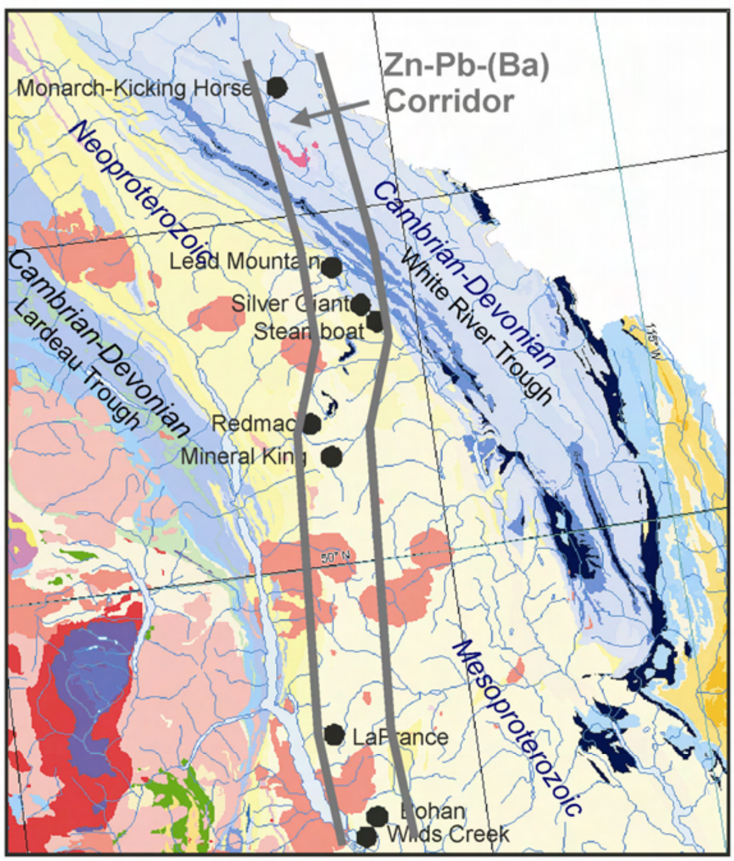

Fig. 4. Map of part of southeastern British Columbia showing major geological features and locations of mineral deposits plotted in Fig. 3. Geological map created by B.C. Geological Survey's MapPlace (http://webmap.em.gov.bc.ca/mapplace/minpot/bcgs.cfm)

New TGI-3 interactive data products at a glance

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ABSTRACT

The Targeted Geoscience Initiative 3 (TGI3) Cordilleran project contains many different components, and each of these components contains different digital datasets. In years past, these datasets were used to make paper maps and were downloadable in their raw form. With TGI3 coming to a close, many of these datasets have being cleaned up and are being released as digital queriable maps and databases. These products allow the user to display and query the data in a plethora of formats to help aid in the exploration of new deposits in the Cordillera. Datasets released thus far include data collected from the Sullivan Mine, Chilcotin Basalts, and Southern Quesnel Terrane, while future releases will include data from the Purcell Basin.

Basement controlled mineralization, intrusions and facies, southeastern British Columbia; "Two for one exploration targets"

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ABSTRACT

Intermittently active old structures in the crystalline basement underlying the deformed and transported rocks of the southeastern Canadian Cordillera have exerted an important influence on the subsequent sedimentary, intrusive, deformation and mineralization history (McMechan, 2010). The most important structures formed during Paleoproterozoic and Archean growth and assembly of the underlying crystalline basement and are oriented transverse to the Cordilleran structural trend (Fig. 1).

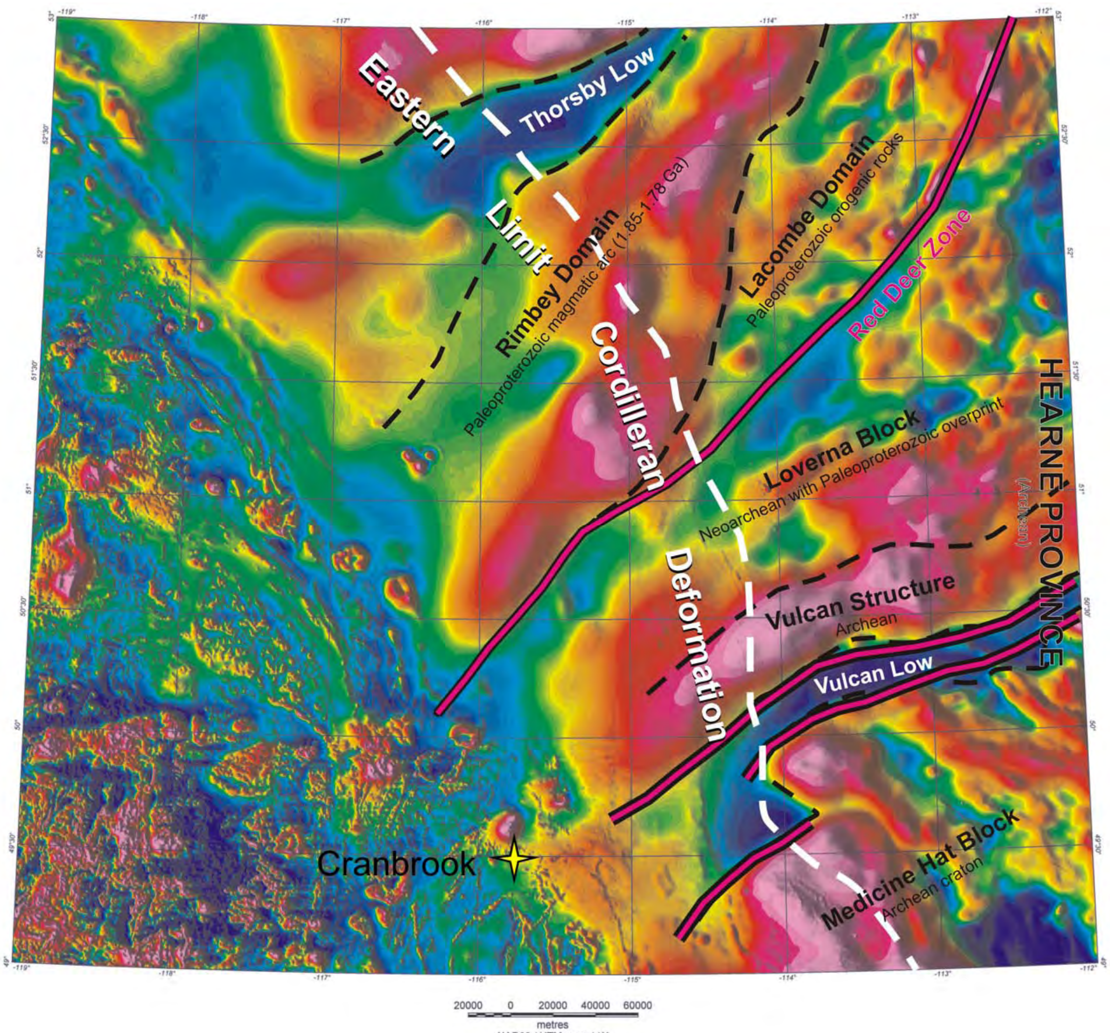

Figure 1. Domain boundaries of the crystalline basement underlying southeastern British Columbia and southwestern Alberta outlined by shaded total magnetic field. Domain boundaries are after Hope and Eaton (2002). Image derived from Canadian Aeromagnetic Database.

Other structures, oriented subparallel to the Cordilleran structural trend, formed during Mesoproterozoic, Neoproterozoic or Cambrian rifting events. Much mineralization in the lower Purcell including the Sullivan Mine formed in areas where both transverse and basin parallel structures were active (Fig. 2). The importance of the transverse Vulcan Low basement domain in localizing mineralization, intrusions and major thickness and facies changes in the southern Purcell Basin has been recognized for some time.

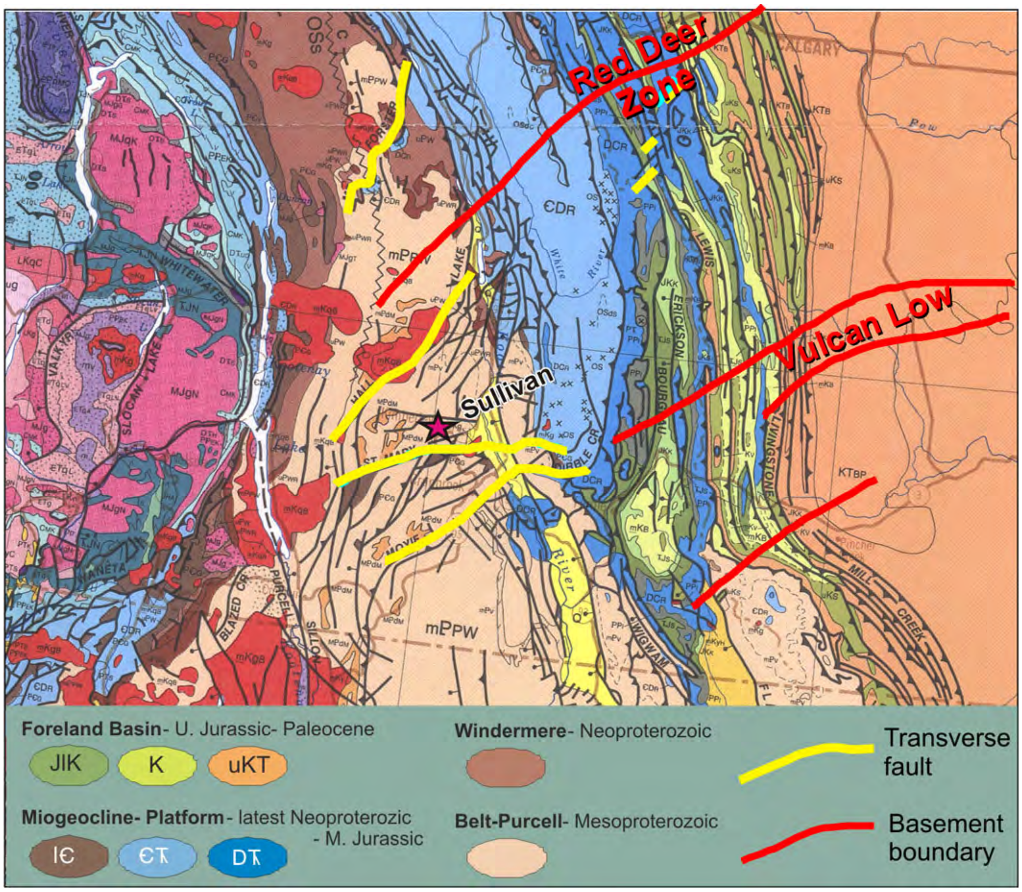

Figure 2. Major basement boundaries in crystalline basement and transverse faults in adjacent Cordillera, southeastern British Columbia and southwestern Alberta. Base map for this and following figure is The Tectonic Assemblage Map of the Canadian Cordillera (Wheeler and McFeely, 1991).

New work suggests a more northern transverse basement structural zone, the Red Deer Zone, at the north end of the Archean Hearne province had a similar effect. In this area, a northeast-trending zone extending across the Rocky Mountains and Purcell Mountains is delineated by facies changes, anomalous northeast-trending faults, Pb-Zn showings, and a cluster of Late Ordovician - Early Devonian diatreme breccia pipes. Features in the eastern Rocky Mountains restore palinspastically to original positions directly above the Red Deer Zone and its along strike projection (Fig. 3). Intermittent activity along this basement structure localized facies changes, intrusions, mineralization and subsequent structural trends in the Rocky Mountains, facies changes in the northern Purcell Basin, and Tertiary normal faults, mineralization and intrusions near Kootenay Lake.

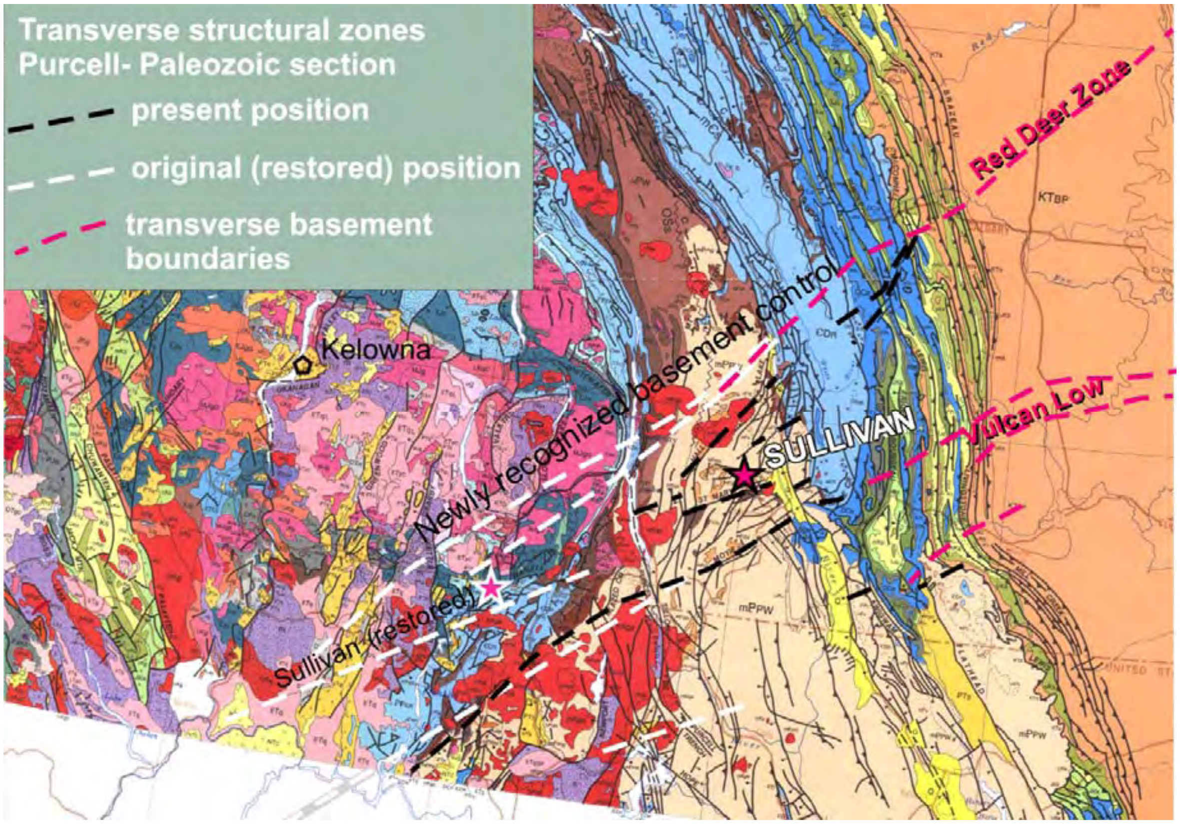

Figure 2. Present and restored (original) positions of major transverse, basement-controlled structural zones in the southeastern Canadian Cordillera.

Transverse basement structures in southeastern British Columbia were intermittently active from Archean to Tertiary time. They form prospective targets for mineral exploration, particularly in preferred mineralization horizons (metallotects) and near structural intersections. Each basement structure provides two exploration opportunities:

1. Along transported exposed structures.
2. Above buried (original) position.

Exploration along exposed and buried traces may be fruitful in the future.

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