

SA Global

CSA Global Canada Geosciences Ltd Suite 610 - 1155 West Pender Street Vancouver, B.C. V6E 2P4

> T +1 604 681 8000 E csacanada@csaglobal.com

Incorporation Number: BC0943947

www.csaglobal.com

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Catchment Analysis Applied to the Interpretation of New Stream Sediment Data

Northern Vancouver Island, Canada (NTS 102I and 92L)

By

Dennis Arne PhD, PGeo (BC), RPGeo (Australia)

> Olivia Brown BSc (Hons)

> > Approved: Dr. D. C. ARNE 34686 BRITISH COLUMBIA SCIEN Dennis Arne Director

For:

Geoscience BC Suite 440 - 890 Vancouver British Columbia, Canada V6C 1J9



Executive Summary

Raw Cu data in stream sediment samples obtained from moss mats on northern Vancouver Island are dominated by the presence of Late Triassic mafic volcanic rocks of the Karmutsen Formation and, to a lesser extent, by the presence of diabase sills of the Mount Hall Gabbro in the Middle to Late Triassic Vancouver Group. These units can effectively be traced using the first principal component from multivariate analysis of the raw geochemical data. High background Cu in these lithological units potentially obscures Cu anomalies associated with exposed porphyry Cu deposits in the region.

New ICP-MS, INAA and fire assay data from 1,725 samples from northern Vancouver Island have been compiled for this study. Sample locations were adjusted to conform to the TRIM drainage where necessary and validated against scanned copies of the original NTS map sheets used for sampling where these adjustments were uncertain. Nested catchments for the samples were delineated automatically from digital elevation data using a procedure developed by the British Columbia Geological Survey.

Using Cu as the main demonstration element, this study illustrates that there are a variety of ways to process raw Cu data in areas strongly influenced by a particular rock type, such as basalt, that has high background Cu associated with it. Copper residuals calculated from the regression of Cu against Al correct for the absorption of Cu onto clay minerals in the samples and partially removes the Cu highs associated with the Karmutsen Formation. Robust Z-score levelling of the log_{10} transformed Cu data by the dominant lithology in the catchments areas, levelling by the presence or absence of basalt, levelling by a weighted background value calculated for each catchment based on the relative proportions of varying lithological units in the catchments, and regression analysis of Cu against the robust principal component that best geochemically defines the distribution of the Karmutsen Formation, all provide broadly similar results. In all cases the high Cu associated with the Karmutsen Formation is suppressed to varying degrees and anomalies associated with known Cu occurrences are emphasized. New Cu anomalies not associated with known Cu occurrences are evident in the data. However, the most effective predictor of known Cu occurrences in the study area is obtained using a weighted sums model calculated from Cu, Mo, Ag and Zn data that have been levelled by the dominant rock type in the catchment areas, plus raw Au data.

The effects of dilution of anomalous geochemical responses in the stream sediment data are evident in plots of both raw and levelled element concentrations plotted against catchment area. Calculated Cu productivities do not offer an improvement on the various levelled products in predicting the distribution of known Cu occurrences in the study area. Visual analysis of the Cu data suggests that the maximum effective catchment area for sampling is 10 km². While nearly 90 % of the catchments are less than this amount, the remaining catchments are considered to have not been effectively sampled, thus providing new exploration opportunities.



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1 Introduction

Geoscience BC has been engaged for many years in the re-analysis of archived sample material from previous regional geochemistry surveys (RGS), as well as in the collection of new samples to cover areas where historical sample coverage was not considered to have been adequate. A number of projects in the past have examined ways to add value to these new regional geochemistry data sets, including the use of catchment analysis to level the geochemical data for dominant bedrock lithological units in the catchments, and also to assess whether the catchment areas used for sampling were appropriate (Arne and Bluemel 2011). Such approaches are designed to identify 2nd- and 3rd-order geochemical anomalies often overlooked during a routine analysis of the raw geochemical data by accounting for the effects of variable background levels for important pathfinder elements due to exposure of different bedrock lithological units in catchment basins, as well as potential metal scavenging by secondary Fe and Mn hydroxides, clays and organics. In this way, the analysis adds value to the existing data sets by providing information not readily available to most prospectors and geologists working for small exploration companies.

The approach to catchment analysis undertaken herein is aligned with the concept of productivity described by Hawkes (1976) and further expanded on by Pan and Harris (1990) and Moon (1999). Bonham-Carter and Goodfellow (1986) demonstrated that catchment lithology was the main control on observed variation in stream sediment data from the Nahanni region of the Yukon Territory. Other effects, such as catchment area, possible adsorption of some elements onto secondary Fe or Mn hydroxides, or onto organic material, and water pH were considered to be minor by comparison. A similar conclusion was reached by Carranza and Hale (1997) in a study of the main controls on stream sediment geochemistry in the Philippines. Bonham-Carter et al. (1987) applied a similar approach to the analysis of stream sediment data from the Cobequid Highlands of Nova Scotia and further concluded that use of the dominant lithology in the catchment basins was not as effective as taking into account the areal extent of all lithological units in the catchment. Heberlein (2013) levelled newly acquired ICP-MS data for two map sheets in the Yukon using dominant bedrock lithology after demonstrating bedrock control on some elements, such as Cu. One of the fundamental assumptions of these approaches is that similar erosion rates affect all lithological units within a catchment area, although this is unlikely to be the case in many instances, particularly in areas of variable relief (Granger and Schaller, 2014).

The investigation by Arne and Bluemel (2011) utilized a simple approach to levelling stream sediment data for catchment geology by using the dominant bedrock lithology. In that study the dominant bedrock lithology was identified in a GIS query of published bedrock geology and catchments derived using an automated analysis of TRIM terrain data by the Geological Survey of British Columbia. Considerable effort on the QUEST-South project was expended in manually validating the locations of 8536 historical RGS samples using archived field maps. In the case of the 721 newly acquired northern Vancouver stream sediment samples available for this study, the locations are assumed to have been well positioned using modern satellite technology. However, the locations of 1120 historical samples collected previously in 1988 needed to be validated against the TRIM hydrology layer.

The approach used by Arne and Bluemel (2011) may not always be appropriate in large catchment basins where multiple lithological units are to be anticipated, as argued by Bonham-Carter et al. (1987),



nor does it account for variable erosion rates within the catchment. A spatially insignificant rock unit may contribute disproportionately to the geochemistry of a stream sediment sample from the catchment if it is relatively enriched in a particular element. A more accurate approach would be to estimate a weighted background value (WBV) for each catchment and element of interest using background values for individual lithological units and applying a weighting to these values based on the proportion of each unit exposed within the catchment. Such weightings assume a constant supply of sediment from each lithology and may require adjustment to account for local variations in relief and erosion weights. Topography and variable weathering effects for different lithological units are no doubt important factors in controlling the geochemical input from each lithology in a catchment basin, but such a detailed study is beyond the scope of the present investigation. An intermediate approach that is computationally efficient is to use the presence of a particular lithological unit or units to assess catchment basins in a pass/fail approach and this may be as effective as using a the entire catchment geology (Bonham-Carter et al., 1987). Although the use of multiple regression analysis to account for variable lithological units within individual catchments (e.g. Bonham-Carter et al., 1987; Carranza, 2009), has been applied in this study, an approach using weighted background values has been favoured as they are intuitively easier to understand.

An alternative approach to the use of catchments on northern Vancouver Island is that used by Sibbick and Laurus (1995). In that study the authors defined buffer zones around intrusions into Bonanza Group rocks and manually calculated catchments were divided into those underlain by background Bonanza Group rocks and those underlain by potentially mineralized Bonanza Group rocks. Threshold values for Au, As and Mo were determined using probability plots for data from the potentially mineralized catchments and then scores calculated for each catchment to determine its potential to host intrusiverelated mineralization. The approach is somewhat similar to the weighted sums approach described by Garrett and Grunsky (2001) but allows for a more empirical selection of elemental score.

The data set selected for evaluation in this project is the moss matt stream sediment data set assembled as part of the Northern Vancouver Island Exploration Geoscience Project by Geoscience BC in cooperation with the Island Coastal Economic Trust. This project consisted of the collection of new samples (Jackaman, 2013) and re-analysis of historical RGS samples from the same area (Jackaman, 2011; 2014). The location of the study area is illustrated in Figure 1 along with the distribution of sample points. Data from this terrain should be ideal for the automated generation of catchment basins. Raw Cu data in the historical RGS data set from Vancouver Island has previously been demonstrated to be a poor predictor of porphyry Cu mineralization within individual catchment basins due to the widespread distribution of mafic volcanic rocks in the region contributing to high background Cu levels (Sibbick, 1994).

This project compares various approaches to estimating background geochemical levels for stream sediment (moss mat) samples from the northern Vancouver Island study area. New Cu anomalies are apparent in the map products generated for this study once the effects of elevated background Cu are addressed. Data for other elements important for mineral exploration that also show variable backgrounds levels related to bedrock geology (e.g. Ni and Ba) or which tend to be easily adsorbed onto the surfaces of secondary Fe and Mn oxides in the stream sediments (e.g. Zn and As), are also easier to interpret in terms of anomalies that might be related to unrecognized mineralization within the catchment basins. It is hoped that the release of this new data set will stimulate further mineral exploration in the study area.



Although this study focuses on developing predictive models for porphyry Cu exploration on northern Vancouver Island, this is not the only mineral deposit type of interest. Copper skarns and precious metal vein deposits also occur in the area (Sibbick, 1994). To this list we would also add potential for magmatic Ni-Cu-PGE mineralization hosted by mafic or ultramafic intrusive rocks. A number of commodity and pathfinder elements for precious metal deposits have been levelled for the dominant lithological unit in the sample catchments and/or regressed against elements with which they show positive correlations, and these results are provided in data files appended to this report. A variety of weighted sums models or additive indices (e.g. Arne and Bluemel, 2011) can be constructed using these data in order to define project-specific predictive thematic maps.



Figure 1. Location of study area showing the distribution of moss mat stream sediment samples reanalyzed and collected as part of the Northern Vancouver Island Exploration Geoscience Project.



2 Methodology

The stream sediment samples from the northern Vancouver Island (NVI) study area were obtained from moss mats. The high flow velocities of many streams in this region meant that very little fine grained material could be recovered through the collection of traditional stream sediment samples from local traps (Gravel and Matysek, 1989). However, moss mats were found to contain abundant fine grained sediment and to have preferentially trapped heavy minerals, and so were the preferred sampling material for both the 1988 and 2012 surveys. The samples were disaggregated after drying to remove the organic material and then the sediment was sieved to -177 μ m.

Historical and recent moss mat sediment geochemical data and sample location metadata were obtained from a variety of Geoscience BC reports (Table 1). Original field and analytical data obtained by Gravel and Matysek (1989) were taken from Geoscience BC Report 2013-11 (Jackaman, 2013). It was discovered part way through the project that the data file used to plot and then validate the 2012 sample locations was corrupted. The UTM coordinates for approximately half the samples in the Field_data worksheet of the spreadsheet GBC_Report2013-11A.xls have become displaced from the correct sample number. The latitude and longitude locations are correct (Wayne Jackaman, pers. comm., January, 2015). This data file has been replaced on the Geoscience BC web site and only the more recent version of the file should be used by those wishing to obtain the original data files upon which this study is based. Time and budget did not permit re-validation of these sample locations. Instead, the incorrect locations were attributed with the correct sample number and the changes validated spatially and through manual checking of the compiled spreadsheet prepared for this project. Approximately 20 % of the total data set was affected by this correction. Every reasonable effort has been made to ensure the integrity of the final data set but anyone using the data in this report should undertake their own validation of sample locations.

Geochemical data from the re-analysis of the original samples by inductively-coupled plasma mass spectrometry (ICP-MS) following an aqua regia digestion at ALS Minerals were also obtained from Geoscience BC Report 2013-11. These data were supplemented by the addition of Pt and Pd data by lead-collection fire assay from the re-analysis of the original RGS samples in Geoscience BC Report 2011-04 (Jackaman, 2011). A total of 721 new moss mat samples were collected for the Northern Vancouver Island Exploration Geoscience Project area in 2012 (Jackaman, 2013). These samples were analyzed using both ICP-MS following an aqua regia digestion at ALS Minerals and by instrumental neutron activation analysis (INAA) at Becquerel Laboratories Ltd. Data on water F contents, pH, and conductivity, as well as sediment LOI and F were also obtained on these new samples. The archived RGS samples were also re-analyzed by INAA at Becquerel Laboratories Ltd, and the results are reported in Geoscience BC Report 2014-03 (Jackaman, 2014). The various sources of data compiled for this study are summarized in Table 1 and the reader is referred to these sources for further analytical details and limits of detection.

Analytical and historical metadata were assembled in a Microsoft Access[™] database. Final merging of the data, including catchments attributed with bedrock geology and percentage of Quaternary sediment, was undertake manually in Microsoft Excel[™] using the master ID number for control. Spot checks of sample details against the original source data files were made to ensure that the integrity of



the data was maintained during this process. Data for 104 duplicate pairs were removed in the final combined data set prior to analysis of the data, leaving 1,736 samples for catchment analysis. Seven of these samples were not re-analyzed due to missing material and so only partial data were available for analysis, four samples were re-samples of sites previously sampled in 1988, and no catchment was delineated for one sample, leaving a total of 1725 samples with complete unique data sets. The assembled data were then validated in ioGAS geochemical assessment software and detection limits set as positive values at ½ the lower limit of detection (LLDs) These LLDs were variable for some of the samples analyzed by instrumental neutron activation (INAA) due to variable and, in some cases, very small sample aliquots. Where reasonable, the below detection values were converted to ½ the LLD. Where the INAA LLDs were quite high due to small sample weight, the LLDs were set at the lowest value for the data set so as not create falsely elevated values as a function of extremely high LLDs.

Source	Data Type	Number	Data			
Geoscience BC Report 2013-11 Appendix B	Original	1120	original field metadata; Au by fire assay with charge weights; LOI, F in sediment & water, U in water, pH			
(MEMPR RGS 21-25)	analyses	1120				
Geoscience BC Report 2011-04	Re-analyses	1120	aqua regia ICP-MS; Pt and Pd by fire assay with charge weights			
Geoscience BC Report 2013-11 Appendix A	New samples	721	aqua regia ICP-MS; INAA with charge weights; LOI, F in sediment & water, pH, conductivity			
Geoscience BC Report 2014-03	Re-analyses	1107	INAA with charge weights			
		1841	Total number of samples			

Table 1. Summary of data sources and type compiled for this project.

Cui (2010) has emphasized the necessity of validating the historical RGS sample locations against the hydrology layer using the current 1:20,000 scale terrain resource information management (TRIM) topographical and hydrological data available in British Columbia, as the entire approach is predicated on the attribution of sample data to the correct watershed. The original RGS sample locations were manually located on NTS 1:50,000 topographic map sheets during field collection and the locations visually read off the map grid. Historical and recent sample locations were compared to the TRIM hydrology on screen and shifted where sample locations lay off stream. Scans of the original NTS 1:50,000 field maps (available from http://propertyfile.gov.bc.ca/) were used to determine the correct drainage line on which to place the sample where there was ambiguity in the sample location. An example of the sort of location adjustments that were made to some of the historical RGS samples is given in Figure 2. In spite of having access to these original field maps, there were still a few samples where the sample location is equivocal.

Catchment basins for the validated sample locations were generated using the automated methodology described in Cui et al. (2009). This approach involves a three-stage computation:

- 1. Identify the root watershed for each stream sediment sample site;
- 2. All watersheds upstream of the root watershed are retrieved; and



3. The upstream watershed boundaries are dissolved to yield a single catchment for each sample.

The approach just described differs from that used by Sibbick (1994). The catchments defined for that analysis were digitized manually from NTS 1:50,000 topographic maps. However, the catchment basins for samples with nested catchments were truncated at the next upstream sample so that some samples are represented only by a sub-catchment area, meaning that the catchment areas for some RGS samples in that study will be underestimated compared to our approach. The contribution of bedrock lithological units to the geochemistry of the stream sediment sample from areas located upstream of other samples on the same drainage system would not be taken into account using these sub-catchments only. A comparison of catchment areas derived using the two methodologies indicates good agreement for the bulk of the catchments, but reveals considerable scatter between a significant number of catchments determined manually using sub-catchments and nested catchments as described by Cui et al. (2009). In some instances the differences are on the order of several orders of magnitude. These differences either reflect the different approaches to evaluating nested catchments or differences in placement of the samples on the two hydrology layers (NTS 1:50,000 vs TRIM). The final validated catchments are illustrated in Figure 3.



Figure 2. An example of a historical RGS sample location adjustment to the current TRIM hydrology data using the original NTS map sheet.





Figure 3. Catchment basins delineated for historical RGS and new moss mat samples from northern Vancouver Island.

Each catchment was then queried against the bedrock geology rock type using the current digital bedrock geology from the British Columbia Geological Survey (BCGS) available at the following web site: http://www.empr.gov.bc.ca/Mining/Geoscience/BedrockMapping/Pages/BCGeoMap.aspx (accessed December 11, 2014). The rock type description field was used, rather than stratigraphic unit, because it contains the most information regarding lithology (Figure 3). The rock type descriptions were then simplified for interpretative purposes using the conversions listed in Table 2. Rock type designations were merged only after it was determined that there were no significant geochemical differences between the groups.

Although the bedrock geology of NVI has been recently mapped in detail by BCGS, the information had not been integrated with the current digital bedrock geology for the province at the time of this study and so this revised geology was not used to attribute the catchment polygons. Much of the improved understanding of the bedrock geology involves new paleontological and geochronological constraints on the ages of individual stratigraphic units. As such, it is anticipated that the revised bedrock geology will have minimal impact on the attribution of major rock types to most catchment areas.



Table 2. Summary of rock types in the project area and example geological units.

Rock Type	Simplified Lithology	Example Units
Basaltic volcanic rocks	Basalt	Karmutsen Formation
Calc-alkaline volcanic rocks	Volcanic rocks	Bonanza Group
Undivided volcanic rocks	Volcanic rocks	Pacific Rim Complex
Marine sedimentary and volcanic rocks	Carbonates	Vancouver Group
Limestone, slate, siltstone, argillite	PB siliciclastics	Parson Bay Formation
Limestone, marble, calcareous sedimentary rocks	Carbonates	Quatsino Group
Undivided sedimentary rocks	Siliciclastics	Nanaimo Group
Mudstone, siltstone, shale fine clastic rocks	H siliciclastics	Harbledown Formation & Daonella Beds
Intrusive rocks, undivided	Intrusives	Westcoast Crystalline Complex
Dioritic intrusive rocks	Diorite	Late Jurassic to Early Cretaceous
Quartz dioritic intrusive rocks	Quartz diorite	Mt. Washington Plutonic Suite
Granodioritic intrusive rocks	Granodiorite	Island Plutonic Suite



Figure 4. Bedrock geology of the NVI study area with the distribution of Quaternary deposits also shown.



The catchment polygons could only be attributed with the percentage of Quaternary material within them using the BCGS Quaternary geology layer. A total of 694 catchments contain some Quaternary material according to the available information, but in only half of those catchments does the amount exceed 5 %. Of these, only 15 catchments contain greater than 70 % Quaternary material and so its influence, as currently mapped, is not considered to be significant. Nonetheless, it was designated as the main lithological unit in the catchments where it was the dominant material.

Details on the origin of the Quaternary material were not readily available aside from the surficial geology map of Kerr (1992) for the Quatsino area, which indicates the presence of a wide variety of materials: fluvial, glaciofluvial, lacustrine, glaciolacustrine, morainal, volcanic, marine and glaciomarine sediments. These various Quaternary deposits will undoubtedly have an influence of the geochemistry of stream sediment samples from the study area, but in the absence of detailed surficial geology for northern Vancouver Island in a format that can readily be queried in a GIS, their potential contributions have not been assessed, aside from the potential for dilution where significant Quaternary material occurs within a catchment area.

The dominant lithology was attributed to each catchment once bedrock geology and percentage of Quaternary material were determined. A number of catchment areas consist of a single lithology based on the available bedrock and Quaternary geology maps. Geochemical data from these catchments was used to estimate background values for Cu. The dominant lithological unit was estimated based on the percentage of each simplified lithology summarized in Table 2. Some lithological units were combined with more common units where insufficient catchments for statistical treatment were represented by some minor lithological units. Finally, each catchment area was attributed as to whether or not it contains basalt. A 5 % threshold value for basalt was used given uncertainties in both the delineation of the catchment boundaries and the bedrock geology. Poorly defined lithological units, such as "volcanic" or "calc-alkaline" have not been used to designate the presence of basalt within the catchments given the absence of clear details on lithology. Basalt is the most common single lithology within most catchments, even without the potential contribution from poorly defined volcanic units. It must be kept in mind that the above process is only a crude estimation of lithology in each catchment area based on the available interpretive map and that there is no allowance for differential erosion from various units within a catchment.

A weighted sums modelling (WSM) approach to particular deposit types can be used to apply *a priori* knowledge about what elements should be associated with a particular style of mineralization (Garrett and Grunsky, 2001). Unlike multivariate methods such as principal component analysis (PCA), WSM allows elements to be weighted by the analyst rather than having the weights dictated by the data set. This allows the results to be biased in a way that can intentionally filter out certain styles of mineralization that would otherwise have a largely overlapping geochemical signature. In this respect, the WSM approach has an advantage over the use of additive indices calculated using levelled data (e.g. Arne and Bluemel, 2011). The approach has recently been applied to RGS data in the Yukon (Heberlein, 2013). However, rather than use raw data as originally done by Garrett and Grunsky (2001), residuals and levelled data will be used in the weighted sums models to be tested for porphyry Cu-Mo-Au deposits on NVI due to the potential effects of scavenging and variable background demonstrated by this study.



3 Geochemical Data Quality

Although data quality for the re-analysis of historical RGS samples and the analysis of new samples collected in 2012 was previously assessed at the time of data compilation, the quality control data were not made publically available, aside from data for field duplicate samples. Therefore, quality control data for a few key elements (Au, PGE, Cu) have been evaluated to provide a basis on which further interpretation of the data can be assessed.

The issue of data precision for the original RGS Au data from the Yukon has previously been noted, most recently by Arne and MacFarlane (2014). Gold was originally determined on the RGS samples from NVI using a lead collection fire assay with a 10 g (and occasionally a 5 g) charge. Data for 656 analytical duplicate pairs were obtained from all RGS samples collected on Vancouver Island in 1988 and 1989. The data for 383 duplicate pairs having average values in excess of 10 ppb (i.e. an order of magnitude above the 1 ppb lower limit of detection for a 10 g charge) are presented in Figure 5. The data clearly suffer from poor reproducibility with an indication of a negative bias in the duplicate analyses. The average coefficient of variation (CoV) for these duplicate pairs is 102%, calculated using the root-mean-squared (RMS) method described by Stanley and Lawrie (2007). This value is virtually identical to the CoV determined from 58 field duplicate samples having average values >10 ppb, and suggests that sub-sampling the 10 g charge for analysis has introduced as much uncertainty into the data as the total uncertainty associated with field sampling, preparation, sub-sampling and analysis.

Gold data obtained from the more recent ICP-MS re-analyses are likely to have even greater variance given the 0.5 g aliquot analyzed and it is recommended that these data not be used. A comparison of INA and ICP-MS Au data from Jackaman (2013) shows a very poor correlation between the two data sets based on analysis of the same samples (Figure 6). The INAA Au analyses are based on an average charge weight of 37.3 g for the 2012 sample analyses and 27.41 g for the re-analyses by INAA. The latter includes a wide range of aliquot weights, from just over 50 g to less than 1 g, so the precision of individual values will be variable. The INAA Au data are assumed to be superior to the original RGS Au data given average aliquots 3 times what was originally analysed, although it is not possible to assess the laboratory precision as data are not available for duplicate INAA analyses. Only 8% of the archived samples re-analysed by INAA had sample weights less than 10 g. Therefore the INAA data will be used to provide the Au values used for this study where available. Historical fire assay data have been used for a total of 87 samples for which insufficient archived material was available for INAA.

Copper data from a total of 169 field duplicate pairs collect across Vancouver Island have been compiled from the re-analysis of the RGS samples reported by Jackaman (2011). These data encapsulate the total uncertainties associated with sample collection, preparation, digestion and analysis. By contrast with the large uncertainties associated with the analytical duplicates for Au described in the preceding paragraphs, the average CoV for Cu is 5.9% based on data from all 169 field duplicate pairs. This compares to an average CoV of 5% for 104 analytical duplicate analyses, indicating that the uncertainty associated with sampling is 3.1% in the case of Cu. This observation may apply to all of the base metals, although not all data have been assessed for the purposes of this project. The reproducibility of the Cu data is considered to be very good.





Figure 5. Comparison of historical Au data from analytical duplicates collected on Vancouver Island in 1988 and 1989 analysed by fire assay.



Figure 6. Comparison of Au data from INAA and ICP-MS from Jackaman (2013).



The quality of the PGE data is also variable depending on which data set is examined. The archived RGS samples for all of Vancouver Island were analysed for Pt and Pd by fire assay using an average charge weight of 22.7 g and lower limits of detection for Pd and Pt of 0.5 and 0.1 ppb, respectively (Jackaman, 2011). PGE data for the new samples collected on northern Vancouver Island in 2012 have been analysed by ICP-MS using a 0.5 g aliquot with lower limits of detection for Pd and Pt of 1 and 2 ppb, respectively. The fire assay PGE data from the archived samples are therefore considered to be superior. The average CoV for 149 field duplicate analyses of Pt by fire assay is 19.2%, mainly because the levels are generally less than 10 ppb and therefore probably reflect background values. Duplicate pairs for those rare samples with anomalous Pt show much greater variance, more along the lines observed in the Au fire assay data. Equal weighting should not be given to all Pd and Pt results from the project area given the possible physical transport of PGE grains in the streams sampled due to their high velocities and therefore the likelihood of data having been obtained from non-representative samples.

4 Results



4.1 Multivariate Statistical Analysis and Potential Scavenging Effects

An important factor to be considered is the possibility of scavenging of cations by secondary iron oxides in the samples. This is known to be an important influence on stream sediment data in areas of low relief (Bonham-Carter and Goodfellow, 1986). Non-parametric Spearman Rank correlation coefficients were calculated for a number of commodity and pathfinder elements in order to determine underlying associations that may influence the distribution of data values (Table 3). Iron, which commonly occurs as a variety of secondary Fe hydroxides and oxides in the surficial environment, shows statistically significant positive correlations with Au, Ag, Al, Co, Cr, Cu, Mg, Mn, Ni, Sb, Zn, P, Ca, Sc, Ti, V, Pt and Pd. Manganese, which also occurs as a variety of secondary oxide phases in the surficial environment, shows statistically significant positive correlations with most of the same elements, excluding V, but with the addition of As, Bi, Mo, Te, Tl, Pb and Hg. Aluminium, which may reflect the amount of clay in the samples or the presence of aluminosilicate minerals, shows positive correlations with Au, Ag, Co, Cr, Cu, Fe, Mg, Mn, Ni, Te, Zn, Hg, Ca, Na, Ti, Sr, V, Sc, Pt and Pd. Loss on ignition (LOI), which can be used as a surrogate for organic C in the absence of C analyses, shows strong positive correlations with Mn and Hg ($r^2 > 0.5$ for n=1,729), with lesser correlations for Ag, Al, Co, Pb and Te. These correlations are also supported by robust statistical methods. Multivariate statistics therefore suggests associations between elements representative of secondary phases known for their scavenging effects of metals, and many of the important commodity and pathfinder elements used in mineral exploration. Alternatively, the positive correlations with major elements such as AI and Fe may reflect the transport of aluminosilicate grains in the high-energy streams that characterize much of the study area. Although cause and effect cannot be demonstrated through correlation, as there are many other processes that might cause apparent correlations within the data (e.g. closure), the possibility that a commodity element such as Cu varies in its concentration as a function of other elements warrants consideration.

Robust principal component analysis using log₁₀-transformed data and a correlation matrix indicates that the most variation in the data (PC1 – 32%) defines a positive pathfinder and commodity element group and a negative mafic association that includes Cu (Figure 7). The positive loadings on PC1 appear to correlate spatially with calc-alkaline volcanic rocks of the Bonanza Group on the western side of NVI, indicating that some of the pathfinder and commodity elements may be influenced by regionally-elevated background values. Similar associations are evident in the data when centred log ratios and a covariance matrix are used instead of the raw data, although the eigenvectors change somewhat for the various elements. PC1 has been inverted so that the mafic association forms positive values that can be gridded to demonstrate the close spatial association of this principal component with the distribution of basalt, primarily the Karmutsen Formation (Figure 8). This observation supports the conclusion of Sibback (1994) that raw Cu data in stream sediment samples from NVI predominantly reflects the presence of mafic rocks in the catchments (Figure 9).





Figure 7. Scaled coordinates for robust principal component 1, northern Vancouver Island.



Figure 8. Gridded percentile image of inverse robust PC1 overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.





Figure 9. Gridded percentile image of raw Cu data overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.

Robust PC2 (20% of variation) has positive values only for Au and Pd, suggesting an association with mode of transport (i.e. mechanical vs. chemical). The majority of elements in this principal component show negative weightings that include elements potentially related to scavenging of metals, including Fe, Mn and Al. A separate scavenging association involving LOI and Mn is suggested by their association with Zn, Co, Sc and Hg in negative robust PC3 (8% of variation). The positive association for robust PC3 includes Sr, W, Na and Cu and may represent mineralization. The lesser PC4 (4% of variation) also appears to be related to possible scavenging effects, with a V-Fe association and an LOI-Pd, Sr, Te, Hg association.

Bivariate plots of potential secondary control elements (Fe, Mn, Al, LOI) have been examined to confirm the correlations indicated by multivariate statistical analysis and to assess variation between elements for catchments dominated by different bedrock lithological units. On this basis, the following elements underwent regression analysis against Al – Co, Cr, Sc, Cu, Ni and Zn. Vanadium was regressed against Fe and Hg regressed against LOI. All data were log₁₀ transformed prior to robust regression and treated separately by lithology group. Residuals were calculated to generate gridded percentile image maps and for inclusion in further calculations. The use of Cu residuals following regression against Al reduces the influence of the Karmutsen Formation on the data (Figure 10) and provides a slightly improved fit to known Cu occurrences. The use of centred log ratios and a covariance matrix reduces the association between Cu and Al somewhat, although a positive association is still evident in the data.





Figure 10. Gridded percentile image of Cu residuals following regression against Al overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.

Although not included in the PCA, water pH does appear to show a statistically significant positive correlation with some metals (i.e. a negative correlation with H ion concentration), including Al, Ag, As, Co, Cu, Cr, Hg, Mn, Ni, Sb, Sc, Tl and Zn. Most pH values from NVI are >6, indicating neutral to alkaline surface waters. Iron is expected to be in the ferric state under such conditions and to possess a net negative charge, making it suitable, along with secondary Mn phases, for adsorption of a variety of cations (McLean and Bledsoe, 1992). Surface water pH largely acts as a control on the solubility of Fe and Mn in solution and, coupled with oxidation state, determines the extent to which secondary hydroxide phases will form. These secondary phases have the capacity to adsorb metals once precipitated and their presence may be indicated by elevated levels of Fe and Mn in samples with high cation concentrations. Thus the effect of water pH is indirectly accounted for through the calculation of residuals following regression analysis against Fe or Mn.

As expected, there is a direct influence on stream pH from the dominant lithological units exposed within the catchment areas, with the carbonates and PB siliciclastics showing the highest pH values and the granodiorite- and quartz diorite-dominated catchments the lowest. Oxidation of sulphide deposits can also act to lower stream pH, but this is often a localized effect resulting in "kill zones" that are neutralized through dilution downstream. The effect is generally associated with massive sulphide deposits.



Note that the gridded percentile images shown in this and in following sections are based on the sample point locations and not the catchment areas. They are therefore meant only as approximations of the geochemical response in the catchment areas represented by the stream sediment samples. Thematic maps constructed using percentile intervals of the various residual and levelled products generated for this report are more appropriate for detailed follow-up of geochemically anomalous samples. A series of such thematic maps has been created for Cu and are appended as separate digital files to this report.



Table 3. Spearman Rank Correlation Coefficients for selected commodity, pathfinder and potential scavenging elements for northernVancouver Island.

	Au	Ag	AI	As	Ва	Bi	Co	Cr	Cu	Fe	Mg	Мо	Mn	Ni	Pb	Sb	Те	ті	w	Zn	Hg	Pt	Pd	LOI
Au	1.00	0.27	0.18	0.02	-0.28	-0.06	0.26	0.34	0.48	0.22	0.27	-0.20	-0.13	0.33	-0.12	-0.01	0.00	-0.22	-0.02	0.04	-0.14	0.29	0.27	-0.20
Ag	0.27	1.00	0.34	0.51	0.21	0.42	0.30	0.29	0.48	0.09	0.27	0.33	0.21	0.32	0.47	0.47	0.46	0.36	0.27	0.51	0.23	0.17	0.21	0.22
AI	0.18	0.34	1.00	0.02	-0.23	-0.14	0.68	0.60	0.65	0.34	0.76	-0.25	0.39	0.70	0.00	0.04	0.13	-0.11	-0.16	0.47	0.16	0.45	0.49	0.25
As	0.02	0.51	0.02	1.00	0.37	0.62	0.08	0.01	0.02	0.10	0.15	0.52	0.22	0.04	0.54	0.86	0.44	0.59	0.28	0.54	0.36	-0.18	-0.22	0.02
Ва	-0.28	0.21	-0.23	0.37	1.00	0.41	-0.36	-0.32	-0.36	-0.24	-0.35	0.52	0.07	-0.33	0.40	0.35	0.24	0.68	0.26	0.22	0.18	-0.42	-0.33	0.12
Bi	-0.06	0.42	-0.14	0.62	0.41	1.00	-0.09	-0.22	-0.12	0.05	-0.13	0.65	0.09	-0.25	0.61	0.54	0.47	0.49	0.45	0.31	0.20	-0.29	-0.32	0.08
Со	0.26	0.30	0.68	0.08	-0.36	-0.09	1.00	0.65	0.64	0.47	0.71	-0.25	0.57	0.75	0.00	0.11	0.15	-0.11	-0.27	0.43	0.27	0.45	0.47	0.24
Cr	0.34	0.29	0.60	0.01	-0.32	-0.22	0.65	1.00	0.67	0.31	0.69	-0.34	0.15	0.89	-0.18	0.04	0.04	-0.20	-0.19	0.27	0.09	0.49	0.50	0.01
Cu	0.48	0.48	0.65	0.02	-0.36	-0.12	0.64	0.67	1.00	0.32	0.63	-0.30	0.07	0.74	-0.12	0.00	0.08	-0.28	-0.03	0.26	-0.05	0.52	0.64	0.01
Fe	0.22	0.09	0.34	0.10	-0.24	0.05	0.47	0.31	0.32	1.00	0.48	-0.08	0.22	0.29	-0.02	0.14	0.04	-0.13	-0.10	0.33	0.00	0.13	0.12	-0.23
Mg	0.27	0.27	0.76	0.15	-0.35	-0.13	0.71	0.69	0.63	0.48	1.00	-0.30	0.32	0.80	-0.09	0.20	0.03	-0.12	-0.15	0.52	0.11	0.39	0.40	-0.05
Мо	-0.20	0.33	-0.25	0.52	0.52	0.65	-0.25	-0.34	-0.30	-0.08	-0.30	1.00	0.10	-0.34	0.55	0.47	0.45	0.62	0.45	0.24	0.26	-0.33	-0.38	0.19
Mn	-0.13	0.21	0.39	0.22	0.07	0.09	0.57	0.15	0.07	0.22	0.32	0.10	1.00	0.27	0.32	0.31	0.25	0.33	-0.26	0.59	0.58	0.13	0.10	0.56
Ni	0.33	0.32	0.70	0.04	-0.33	-0.25	0.75	0.89	0.74	0.29	0.80	-0.34	0.27	1.00	-0.16	0.09	0.05	-0.14	-0.26	0.41	0.15	0.53	0.56	0.07
Pb	-0.12	0.47	0.00	0.54	0.40	0.61	0.00	-0.18	-0.12	-0.02	-0.09	0.55	0.32	-0.16	1.00	0.50	0.43	0.53	0.23	0.45	0.35	-0.11	-0.26	0.31
Sb	-0.01	0.47	0.04	0.86	0.35	0.54	0.11	0.04	0.00	0.14	0.20	0.47	0.31	0.09	0.50	1.00	0.42	0.60	0.18	0.59	0.45	-0.16	-0.17	0.07
Те	0.00	0.46	0.13	0.44	0.24	0.47	0.15	0.04	0.08	0.04	0.03	0.45	0.25	0.05	0.43	0.42	1.00	0.40	0.18	0.32	0.35	-0.03	-0.07	0.30
тΙ	-0.22	0.36	-0.11	0.59	0.68	0.49	-0.11	-0.20	-0.28	-0.13	-0.12	0.62	0.33	-0.14	0.53	0.60	0.40	1.00	0.15	0.45	0.44	-0.31	-0.29	0.27
w	-0.02	0.27	-0.16	0.28	0.26	0.45	-0.27	-0.19	-0.03	-0.10	-0.15	0.45	-0.26	-0.26	0.23	0.18	0.18	0.15	1.00	-0.01	-0.12	-0.20	-0.22	-0.10
Zn	0.04	0.51	0.47	0.54	0.22	0.31	0.43	0.27	0.26	0.33	0.52	0.24	0.59	0.41	0.45	0.59	0.32	0.45	-0.01	1.00	0.41	0.03	0.10	0.18
Hg	-0.14	0.23	0.16	0.36	0.18	0.20	0.27	0.09	-0.05	0.00	0.11	0.26	0.58	0.15	0.35	0.45	0.35	0.44	-0.12	0.41	1.00	0.03	-0.12	0.52
Pt	0.29	0.17	0.45	-0.18	-0.42	-0.29	0.45	0.49	0.52	0.13	0.39	-0.33	0.13	0.53	-0.11	-0.16	-0.03	-0.31	-0.20	0.03	0.03	1.00	0.32	0.08
Pd	0.27	0.21	0.49	-0.22	-0.33	-0.32	0.47	0.50	0.64	0.12	0.40	-0.38	0.10	0.56	-0.26	-0.17	-0.07	-0.29	-0.22	0.10	-0.12	0.32	1.00	0.17
LOI	-0.20	0.22	0.25	0.02	0.12	0.08	0.24	0.01	0.01	-0.23	-0.05	0.19	0.56	0.07	0.31	0.07	0.30	0.27	-0.10	0.18	0.52	0.08	0.17	1.00



4.2 Effects of Variable Geochemical Background

Visual assessment of Tukey plots in which the main commodity and pathfinder elements have been attributed by the dominant lithological unit determined for each catchment confirms the effect of basalt on the concentration of raw Cu values within the samples (Figure 11), as well as on the spatial distribution of the raw Cu data (Figure 9). Some of the unit H-siliciclastic rocks also have elevated Cu, probably due to the presence of diabase sills of the Mount Hall Gabbro that exist within the Daonella Beds of the Vancouver Group. This particular unit appears to be elevated in Cu compared to the Harbledown Formation, with which it shares similar sedimentary lithological units but lacks the sills of the Mount Hall Gabbro. The H-siliciclastics, along with PB-siliciclastic sediments of the Parson Bay Formation, also have elevated Mo. In all cases where the Cu data have been modified, a prominent Cu high persists approximately mid-way between Tahsis and Sayward. This area is broadly coincident with the deep water, fine-grained siliciclastic rocks of the Daonella Beds and associated mafic intrusive rocks of the Vancouver Group. These are likely the source of elevated Cu within this unit that becomes more prominent as the effects of Cu associated with the Karmutsen Formation are supressed. There are several approaches to subduing the effect of high background Cu in these mafic lithological units as described below.

Z-score levelling (following a log₁₀ transformation) of the Cu data by dominant lithology reduces the influence of the Karmutsen Formation on the spatial distribution of levelled Cu data while preserving the presence of statistical outliers (i.e. geochemical anomalies; Figure 12). The use of robust Z-score levelling, in which the mean is replaced by the median and the standard deviation replaced by the interquartile range multiplied by 0.7413, has a similar effect on the Cu data. The result of this levelling approach are displayed in Figure 13 overlain by the distribution of the Karmutsen Formation and with the locations of known Cu occurrences shown. A comparable result is obtained simply by levelling the Cu data by the presence or absence of >5% basalt in the catchment area (Figure 14). In both cases knowledge of the distribution of the main lithological units within the catchment from which the sample was obtained is required to successfully remove the effects of variable background. Simple Z-score levelling of the data is not sufficient.

A more reliable estimate of Cu values derived from the various bedrock lithological units is obtained from catchments dominated by a single lithology. Statistical summaries for those lithological units that comprise more than 90% of the catchment area are presented in Table 4. There are insufficient data to constrain background levels for catchments dominated by quartz diorite, and the threshold was reduced to 70% for the PB siliciclastics lithological grouping and Quaternary material in order to obtain enough samples to constrain background. Median values have been used to provide a robust estimate of the background average and an estimate of the standard deviation has been obtained from the interquartile range multiplied by 0.7413. These values have been used to calculate a robust weighted background value (WBV) for Cu in each catchment based on the percentages of each bedrock lithology estimated for the catchments, with the proportional robust uncertainties for the WBV from each major lithological group summed following conversion to variances. The square root of the summed variances was then taken as a robust estimate of the standard deviation of the WBV. A robust Z-score was then calculated for Cu from each sample, defined as (value-WBV)/standard deviation estimate. These values are plotted in Figure 15 overlain by the distribution of the Karmutsen Formation and with known Cu occurrences shown. The results are very similar to those obtained through levelling of the Cu data by the dominant catchment lithology or by the presence or absence of basalt.





Figure 11. Summary of trace element compositions for samples attributed by the dominant lithological unit within the catchment.





Figure 12. Summary of trace element compositions for samples Z-score levelled by the dominant lithological unit within the catchment following a log₁₀ data transformation.





Figure 13. Robust Z-score Cu levelled by dominant lithology in the catchments overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.

Simplified Lithology	Median Cu (ppm)	StdDev Estimate (ppm)
Basalt	110	55.8
Volcanic	39	16.2
Granodiorite/Quartz Diorite	24	17.3
Intrusives	49	27
Carbonates	37	17
Siliciclastics	40	16.9
PB Siliciclastics	40	16.9
H Siliciclastics	110	55.8
Quaternary	14	13.2

Table 4. Robust estimates of average Cu contents and standard deviations.





Figure 14. Robust Z-score Cu levelled by the presence or absence of basalt in the catchment overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.

A similar result to the WBV Z-scores is also obtained through multiple regression of the Cu data against the various percentages of the lithological units inferred for each catchment, as recommended by Bonham-Carter et al. (1987) and Carranza (2009), and then plotting the Cu residuals (not illustrated). This occurs in spite of the observation that coherent correlations are only apparent for a few of the major lithological units, such as basalt or granodiorite, and has the advantage of being computationally efficient.

Finally, the Cu data were Log₁₀ transformed and regressed against the robust principal component that appears to most clearly define the enrichment of Cu and other elements of mafic association in the Karmutsen Formation, robust PC1, or in this instance the inverse of PC1. The results (Figure 16) also provide an acceptable product in that they supress the effects of elevated Cu associated with the Karmutsen Formation, although there are differences in detail with some of the other levelled and residual products.

The results of the various data treatment approaches for Cu from the NVI study area are illustrated as gridded percentile images in Figure 17 along with raw Cu data for comparison. The persistence of an anomaly when the Cu data are treated using a variety of approaches should be taken as an indication of robustness. The five data treatment approaches tested (and their variants) have successfully supressed the effects of elevated Cu in the Karmutsen Formation to varying degrees:



- 1. Regression analysis of Cu as a variable dependent on the Al content of the sample;
- 2. Z-score levelling of log₁₀ data transformation and robust Z-score levelling of the Cu data using the dominant lithology identified in each catchment;
- 3. Robust Z-score levelling of the presence or absence of basalt;
- 4. Robust Z-score levelling of Cu data against the weighted background value (WBV) from each catchment (similar to multiple regression analysis of Cu against catchment geology); and
- 5. Regression of the Cu data against the inverse of PCR1, the robust principal component that best geochemically defines the distribution of the Karmutsen Formation.



Figure 15. Robust Z-score Cu levelled by the weighted background value (WBV) for Cu in each in the catchment overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.

Prominent geochemical anomalies associated with significant Cu deposits near Port Alice and to the west of Port McNeill that are evident in the raw geochemical data are also observed in all the data treatments. The effect of supressing the effects of elevated Cu background in catchments containing the Karmutsen Formation is to raise the relative magnitude of Cu anomalies associated with known Cu occurrences in the NVI study area and to generate new Cu anomalies not previously well defined.

It is important to note that areas of anomalous Cu response following processing of the data may have several causes. The bedrock geology may not be accurate at the scale of some small catchments, or



minor lithological units may be present that are not identified on a regional scale. A geochemically distinct lithological unit may be small in areal extent but eroding at a greater rate than other lithological units in the catchment or occur in the immediate vicinity of the sample site, and so that its contribution to the geochemistry of the stream sediment sample may be disproportionate to its exposure. Anomalous Cu responses may also be associated with previously unknown mineralization, although it should not be assumed that an anomaly is necessarily indicative of such.



Figure 16. Residuals of Cu after regression against the inverse of PC1 overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.





Figure 17. Comparison of gridded percentile plots of raw Cu data (upper left) with the results from various data treatment methodologies discussed in the text.



4.3 Effect of Catchment Area

The response of anomalous metal within a particular catchment will be a function of a variety of influences, including the size of the catchment, the metal content and the area of an exposed mineral deposit within the catchment, and the background content of the metal of interest in the catchment (Hawkes, 1976). In most cases the size of an exposed mineral deposit is small relative to the area of the catchment and thus the catchment area becomes the most important factor controlling dilution of the geochemical response. Therefore, those terms related to exposed mineralization (which are unknown in any case) can be ignored and the difference between the observed value and the catchment background value divided by the catchment area to calculate a value known as the productivity of the stream. We have previously demonstrated that a robust Z-score derived from the WBV provides an improved response for the Cu data from NVI by correcting for the effects of variable background, namely the presence of the Karmutsen Formation basalts. This value has been used to calculate productivity values for the NVI catchments (Figure 18). The resulting product differs somewhat in detail from the previous data treatments that did not take catchment area (i.e. dilution) into account.

Productivity analysis also allows for a maximum catchment area for sampling to be derived from the equation given constraints on the exposed mineral deposit's contribution to the overall metal content of a stream sediment sample for a given catchment. That is not the preferred approach where data are already available. A simple plot of raw or levelled geochemical data plotted against catchment area (Figure 19) empirically demonstrates the decay of metal content in stream sediment samples as a function of increasing catchment area (i.e. dilution). This observation in fact provides one of the rationales for the selection of sites for continent-scale drainage sampling programs that seek not to detect mineral deposits, but to define broad scale, regional geochemical background. The manner in which metal responses decay varies from element to element and will be dependent upon the mode of transport (mechanical vs. hydromorphic) and the effectiveness of both chemical and physical traps along the drainage path.

Invariably, prominent geochemical anomalies are found in small catchments where the effects of dilution are minimal. Geochemical values generally decay in an exponential fashion with increasing catchment area to the extent that samples collected from large catchment areas do not adequately test for the presence of mineralization within that catchment. Samples lying above this decay curve are anomalous in metal for the size of the catchment and warrant further investigation, although data corrected for variable background should be used for the purposes of identifying whether these may be due to a bedrock effect. The maximum catchment area to be sampled can be estimated for different elements, but for Cu, a catchment area of 10 km² appears to adequately capture most samples with elevated WBV Z-scores above a regional background threshold (Figure 20).





Figure 18. Gridded percentile map of productivity values calculated for Cu overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.

Once a maximum catchment area has been determined for a particular element in order to define effective sampling coverage, a thematic map of those areas which have not been adequately sampled at this density can be produced (Figure 21). These regions represent opportunities for further exploration and discovery. The interpreted maximum catchment area of 10 km² for effective sampling for Cu exceeds the median catchment area of 2.8 km² for the study area, but there are still a significant number of catchments with areas >10 km², even when the in-fill sampling carried out by Geoscience BC in 2012 is taken into account. However, the density of sampling for the NVI project area is not typical of most RGS programs, leaving considerable scope for areas that have been under-sampled elsewhere. The original RGS programs utilized a particular density of sample points for each map sheet, and this may not have always produced an effective coverage of all areas, depending on the drainage pattern.





Figure 19. Bivariate plot of selected metals plotted against catchment area.



Area_km2 : Cu_WBV_Z-score



Figure 20. Bivariate plot of Cu robust Z-score levelled by WBV Cu plotted against catchment area.



Figure 21. Distribution of catchments >10 km² to highlight areas potentially under-sampled for Cu.



4.4 Weighted Sums Modelling

The WSM for porphyry Cu exploration used the following elements, with their weightings in parentheses: Cu (3), Mo (2), Ag (1), Au (1) and Zn (1). Robust Z-score levelled data adjusted for dominant lithology in the catchments were used instead of raw data for all elements other than Au, which typically shows minimal lithological control unless it is an important factor in Au mineralization. The results of this model are shown in Figure 22.

The fit to known Cu occurrences, particularly past producers and prospects, is an improvement over products based on Cu data alone. In particular, the prospects approximately 20 km west of Port McNeill are not evident in the Cu data but have a strong Mo response that is included in the WSM. The use of several levelled elements therefore has the potential to provide a more reliable indication of mineralization, but at the cost of including commodity or pathfinder elements common to other mineral deposit types that may give rise to unintended anomalies.

This model approach can also be adjusted for the effects of dilution by multiplying the WSM scores by catchment area in an approach similar to that used to calculate Cu productivities. The resulting map provides an even better fit to the known occurrences than the porphyry Cu WSM alone and is included with the accompanying percentile catchment maps.



Figure 22. Gridded percentile map of the porphyry Cu WSM overlain by the mapped distribution of Karmutsen Formation and known Cu occurrences.



5 Conclusions

Using Cu as the main demonstration element, this study has illustrated that there are a variety of ways to level raw Cu data in an area strongly influenced by a rock type, such as basalt, that has high background Cu associated with it. Copper residuals from the regression of Cu against Al infer the absorption of Cu onto clay minerals in the sample and effectively remove the Cu highs associated with the Karmutsen Formation. Levelling the raw Cu data by the dominant lithology in the catchment areas, the presence or absence of basalt, a weighted background value calculated for each catchment, or by the robust principal component that best geochemically defines the distribution of the Karmutsen Formation all provide similar results. The high Cu associated with the Karmutsen Formation is suppressed and Cu anomalies associated with known Cu occurrences are emphasized, although there are differences in detail. What is clear from this investigation is that raw element data for some commodity and important pathfinder elements may be strongly influenced by the spatial distribution of particular rock types within a survey region and that some treatment of the raw geochemical data is required to obtain maximum value from the data. Which data treatment is selected may depend upon the elements and mineral deposits under consideration, as well as personal preference. Any approach should be validated against known mineral occurrences similar to those being sought if possible.

Those elements that require levelling for bedrock/background effects and/or regression analysis should be identified through exploratory data analysis and appropriate data treatments applied. There is no "boiler plate" approach to the interpretation of geochemical data and each methodology must be evaluated on its merits. In this regard the treatment of geochemical data should be approached more like geophysical data where it is widely accepted that raw data may have limited interpretative usefulness until they have been processed using a variety of mathematical treatments. This data processing is done to highlight the effects sought by the mineral explorer and to remove potential interferences. The mineral exploration industry needs to progress the interpretation not only of publically-available regional geochemical data sets, from which there is still much value to be gained, but also of proprietary data sets that may have seen limited interpretation. Obvious geochemical anomalies were readily apparent in the original RGS data sets and most have been investigated, with numerous mineral deposits being found. Future discoveries will depend on the recognition of subtle 2ndand 3rd-order geochemical anomalies generated by poorly exposed mineralized systems. The ability to quickly delineate catchment basins using readily available, automated software packages (provided the samples are accurately located and a digital terrain model of moderate to high resolution is available), coupled with the capacity to easily interrogate those catchments for their lithological and other geographic information means that relatively sophisticated treatments of raw geochemical data are readily available and easily employed.

Only a limited number of map products have been generated for this report. These have been designed to illustrate the relative effects of different data processing options for Cu, as this is the commodity element most affected by the presence of basalt in many of the sample catchments. Digital data files that accompany this report contain the catchment polygons as well as the levelled and residual data for a number of additional elements for which gridded percentile raster maps have also been generated.



These data are available for importation into a variety of GIS platforms, allowing the user to generate their own products, including thematic maps using the catchment polygons.



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7 References

ARNE, D.C. & BLUEMEL, E.B. 2011. Catchment Analysis and Interpretation of Stream Sediment Data From QUEST South, British Columbia. Geoscience BC Report 2011-5. URL <u>http://www.geosciencebc.com/s/2009-023.asp</u> [October 2014].

ARNE, D.C. & MACFARLANE, B. 2014. Reproducibility of gold analyses in stream sediment samples from the White Gold Districts and Dawson Range, Yukon Territory, Canada. Explore 164, 1-11, URL < http://www.appliedgeochemists.org/index.php/publications/explore-newsletter> [October 2014].

BONHAM-CARTER, G.F & GOODFELLOW, W.D. 1986. Background corrections to stream geochemical data using digitized drainage and geological maps: Application to Selwyn Basin, Yukon and Northwest Territories. *Journal of Geochemical Exploration*, **25**, 139-155.

BONHAM-CARTER, G.F., ROGERS, P.J. & ELLWOOD, D.J. 1987. Catchment basin analysis applied to surficial geochemical data, Cobequid Highlands, Nova Scotia. *Journal of Geochemical Exploration*, **29**, 259-278.

CARRANZA, E.J.M. 2009. Geochemical Anomaly and Mineral Prospectivity Mapping in GIS, <u>In</u> M. Hale (ed). Handbook of Exploration and Environmental Geochemistry **11**, 115-144

CARRANZA, E.J.M. & HALE, M. 1997. A catchment basin approach to the analysis of reconnaissance geochemicalgeological data from Albay Province, Philippines. *Journal of Geochemical Exploration*, **60**, 157-171.

CUI, Y. 2010. Regional geochemical survey: Validation and refitting of stream sample locations. In: Geological Fieldwork 2010, BC Ministry of Forests, Mines and Lands, Paper 2011-1, 169-179, URL < http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork/Pages/GeologicalFieldwork2010 .aspx> [October 2014].

CUI, Y., ECKSTRAND, H. & LETT, R.E. 2009. Regional geochemical survey: Delineation of catchment basins for sample sites in British Columbia. In: Geological Fieldwork 2008, BC Ministry of Energy, Mines and Petroleum Resources, Paper 2009-1, 231-238. URL <

http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork/Pages/GeologicalFieldwork2009 .aspx> [October 2014].

GARRETT, R.G. & GRUNSKY, E.C. 2001. Weighted sums – knowledge based empirical indices for use in exploration geochemistry. *Geochemistry: Exploration, Environment, Analysis*, **1**, 135–141.

GRANGER, D.E. & SCHALLER, M.2014. Cosmogenic nucleides and erosion at the watershed level. *Elements*, **10**, 369-373.

GRAVEL, J.L. & MATYSEK, P.F. 1989. 1988 regional geochemical survey, northern Vancouver Island and adjacent mainland (092E, 092K, 092L, 102I). In: Geological Fieldwork 1988, BC Ministry of Energy, Mines and Petroleum Resources, Paper 1989-1, 585-591. URL <

http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork/Pages/GeologicalFieldwork1988 .aspx> [October 2014].



HAWKES, H.E. 1976. The downstream dilution of stream sediment anomalies. *Journal of Geochemical Exploration*, **6**, 345-358.

HEBERLEIN, D.R. 2013. Enhanced interpretation of RGS data using catchment basin analysis and weighted sums modelling: examples form map sheets NTS 105M, 105O and part of 105P. Yukon Geological Survey, Open File Report 2013-15.

JACKAMAN, W. 2011. Regional Stream Sediment and Water Geochemical Data, Vancouver Island, British Columbia (NTS 92B, C, E, F, G, K, L &102I). Geoscience BC Report 2011-4. URL < <u>http://www.geosciencebc.com/s/2011-04.asp</u>> [October 2014].

JACKAMAN, W. 2013. Regional Stream Sediment and Water Geochemical Data, Northern Vancouver Island, British Columbia. Geoscience BC Report 2013-11. <<u>http://www.geosciencebc.com/s/Report2013-11.asp</u>> [October 2014].

JACKAMAN, W. 2014. Regional Stream Sediment Geochemical Data, Sample Reanalysis (INAA), Northern Vancouver Island, British Columbia. Geoscience BC Report 2014-03. URL < http://www.geosciencebc.com/s/Report2014-03.asp> [October 2014].

KERR, D.E. 1992. Surficial geology of the Quatsino area. British Columbia Geological Survey Open File 1992-6.

MCLEAN, J.E. & BLEDSOE, B.E., 1992. Behaviour of metals in soils. United States Environmental Protection Agency, EPA/540/S-92/018.

MOON, C.J. 1999. Towards a quantitative model of downstream dilution of point source geochemical anomalies. *Journal of Geochemical Exploration*, **65**, 111-132.

PAN, G. & HARRIS, D.P. 1990. Quantitative analysis of anomalous sources and geochemical signatures in the Walker Lake quadrangle of Nevada and California. *Journal of Geochemical Exploration*, **38**, 299-321.

SIBBICK, S.J. 1994. Preliminary Report on the Application of Catchment Basin Analysis to Regional Geochemical Survey Data, Northern Vancouver Island (*NTS 92L/03,04,05 and 06*). In: Geological Fieldwork 1993, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1994-1, 111-117. URL < <u>http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork/Pages/GeologicalFieldwork1993</u> <u>.aspx</u>> [October 2014].

SIBBICK, S.J. & LAURUS, K.A. 1995. Integrated Geological and Geochemical Map for the Prediction of Intrusionrelated Mineralization, Northern Vancouver Island. *B.C. Ministry of Energy, Mines and Petroleum Resources*, <u>Open</u> File 1995-12. URL <

http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/OpenFiles/1995/Pages/1995-12PredictionExample.aspx >[December 2014].

STANLEY, C.R. & LAWIE, D. 2007. Average relative error in geochemical determinations: Clarification, calculations and a plea for consistency. *Exploration and Mining Geology*, **16**, 267–275.



Appendix 1 List of Files

GBC Report 2015-4 NVI ioGAS export.xlsx

GBC Report 2015-4 NVI Data.xlsx

GBC Report 2015-4 NVI Catchments Cu Percentiles Shapefile – folder (see conversion table below)

GBC Report 2015-4 NVI Geotiff images - folder

GBC Report 2015-4 NVI Thematic Percentiles Catchment Maps – folder

GBC Report 2015-4 NVI Report Figures – folder

Shapefile Header	Accompanying Map Name	Description
L_cu_lithz	CuppmZLogDomLith	Log_{10} Cu Z-score levelled by dominant lithology
L_cu_bslt	CuppmZRobBasPresent	Cu levelled by the presence or absence of basalt
R_cual_log	ResidCuLogAl	Log ₁₀ Cu residuals regressed against Al
L_cu_wbv	None	Cu weighted background values
L_cuwbcz	CuWBVZScore	Cu weighted background value Z-scores
Cu_product	CuProductivity	Cu productivity values
R_cu_pc1	ResidCuICPppmLogPC1	Log ₁₀ Cu residuals regressed against inverse PC1
L_cu_lithr	CuppmZRobDomLith	Cu Robust Z-score levelled by dominant lithology
Cu_sd_ppm	None	Standard deviation estimate for WBV
L_cu_pc1	None	Cu levelled against PC1
Cu-zrob	None	Cu robust Z-score levelled
Wsmrob	None	Robust Weighted Sums Model
Wsm	PorphyryCuWSM	Porphyry weighted sums model
Sr_culog	None	Standardized log ₁₀ Cu residuals regressed against inverse PC1
Wsm_area	CuWSMArea	Porphyry weighted sums model X catchment area

Conversion table for shapefile headers and associated map products