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Enhanced interpretation of regional stream sediment geochemistry from Yukon: catchment basin analysis and weighted sums modeling

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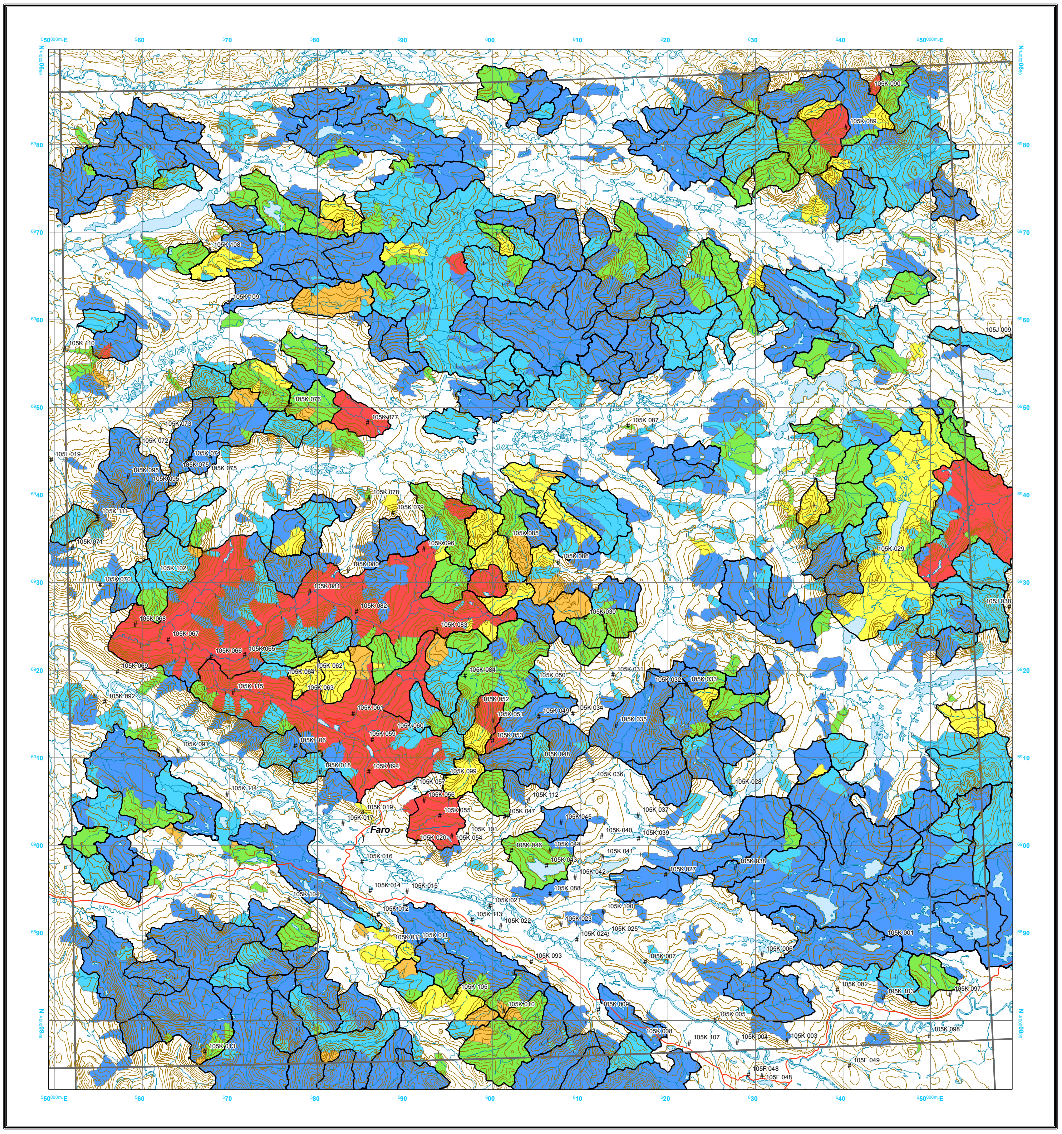

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Cover photo: Weighted sums model of stream sediment geochemical data levelled by dominant geology (NTS 105K): SEDEX Zn-Pb-Ag deposits.

ABSTRACT

Geochemical data from regional geochemistry survey samples from Yukon have undergone exploratory data analysis and principal component analysis. The results of these analyses clearly demonstrate geological control on the distribution of a number of important commodity and mineral deposit pathfinder elements. Catchment basins have been delineated for the samples and the dominant simplified geological unit in each catchment basin used to level the geochemical data where appropriate. Levelling the geochemical data in this fashion generally fails to fully account for enrichments in many commodity and mineral deposit pathfinder elements in the bedrock due to practical limitations on the resolution of the mapping and knowledge of the relative contributions of different geological units, although the resulting data interpretation is an improvement on one based solely upon raw geochemical data. Weighted sums models have been generated for the deposit types that either exist within the individual map areas covered by this report or are considered by the authors to be of exploration significance. Separate catchment maps showing the distribution of stream water pH and the concentration of elements inferred to have accumulated through hydromorphic dispersion are also provided. An additional series of maps has been generated to display weighted sums models calculated using regression of commodity and mineral deposit pathfinder elements against those principal components containing the same elements that show the strongest spatial associations with bedrock geology. Both model types have been iteratively tested using known mineral occurrences in the relevant map areas and, for the most part, are compatible with the distribution of known mineralization where sampling coverage is adequate. Geochemical anomalies unrelated to known mineral occurrences are evident in both data sets and provide possible targets for further investigation.

INTRODUCTION

Regional stream sediment and water geochemistry remain an important tool in mineral exploration. While maps of point data may indicate general areas of anomalism they do not readily allow for assessment of key processes that dictate the composition of the stream sediment (Heberlein, 2013). This report describes the methodology used in the assessment of geochemical data from the recent re-analysis of archived regional geochemical survey (RGS) stream sediment samples through the use of catchment basin analysis and weighted sums modeling. A series of new maps and supporting data files for individual NTS map sheets are generated to highlight catchment basins that show geochemical responses consistent with a variety of base and precious-metal deposit types. Throughout the course of this project, approximately 2/3 of Yukon will be assessed encompassing various geologic terranes including parts of the Selwyn basin and Cassiar Platform, and the Slide Mountain, Yukon-Tanana, Stikinia, Quesnellia, Cache Creek, Kluane and Wrangellia terranes.

The application of catchment analysis for interpretation of stream sediment data is a well-established methodology (Carranza, 2009). Important aspects to be considered include the effects of dilution in catchment basins of differing areas, the influence of variable bedrock lithology on geochemical background values, the potential effects of scavenging of metals onto secondary Fe and Mn-oxides or organic matter, as well as the influence of stream water pH and Eh which control the solubilities of many metals (Hawkes, 1976; Pan and Harris, 1990; Bonham-Carter and Goodfellow, 1986; Carranza and Hale, 1997 and Bonham-Carter *et al.*, 1987; Moon, 1999; Carranza, 2009). The main conclusion of many of these studies was recognition of the importance of bedrock geology as the main control on stream sediment geochemistry. An element such as Cu, which is elevated in mafic lithological units, may require correction for bedrock effects in order to reveal subtle anomalies associated with Cu mineralization (*e.g.*, Sibbick, 1994; Arne and Brown, 2015), whereas the precious metals show only minor variations between differing bedrock lithological units and correction for variable bedrock controls is less important.

As described by Garrett and Grunsky (2001) and employed by Heberlein (2013) and Arne and Brown (2015), weighted-sums modeling (WSM) is a multivariate technique that can be used for the interpretation of geochemical data to aid mineral exploration. WSM is a user-driven approach where importance rankings are assigned to selected variables (elements or element ratios) based on an understanding of mineralogical and chemical characteristics of a target deposit type. Importance rankings can be positive or negative depending on whether a variable is expected to be high or low in a given deposit type, respectively. For a given model a range of importance rankings are used based on assumptions of which elements are more or less indicative of a deposit type.

METHODOLOGY

The geochemical data used in these assessments, as well as associated field descriptions and reports, were acquired from the Yukon Geological Survey (YGS) and/or Geological Survey of Canada (GSC) websites. The original geochemical data, which includes loss-on-ignition (LOI) and water pH data (Garrett, 1974), and the new inductively-coupled plasma mass spectrometry (ICP-MS) data were merged into one master database. ICP-MS data do not provide complete coverage for all maps sheets, as archived material was not always available for re-analysis. Two data subsets are used in this evaluation where ICP-MS data are incomplete. The first subset ("combined") incorporates old and new data to ensure maximum sample coverage, whereas, the second subset ("ICP") includes only samples with complete ICP-MS data. Where differences in survey year and/or analytical method were considered significant, the original data were first corrected using linear regression analysis. Geochemical data must exist for all selected elements for a weighted sums score to be calculated for a given sample. In the case where historical analyses do not exist for a given element (*i.e.*, Bi, Tl, Te) and archived material were not available for re-analysis for a small number of samples, the median value of the ICP-MS data has been used. Such an approach is computationally expedient compared to imputing missing values from multiple regression analysis and is not considered to be significant given that the elements impacted by this approach are pathfinder rather than commodity elements. The pathfinder elements are given low importance rankings and thus have a small influence on calculated WSM scores. This measure was undertaken to ensure maximum coverage of the WSM.

Catchment basins were provided by the YGS using an automated routine in ArcMap™ based on 1:50 000 scale digital elevation data (Fig. 1). Catchments were constructed in such a way that a watershed for a given sample encompasses the entire upslope region including watershed(s) of other upstream samples (*i.e.*, nested catchments). Inherently, this routine requires that each sample point coincides with a stream polyline. This was not always the case using the historical sample locations as they were derived by manual measurement of coordinates on historical 1:250 000 scale topographic maps. As such, sample points were moved to the closest stream polygon using the 'nearest' function in ArcMap™. Additionally, to ensure that each sample lies on the correct watershed the updated sample locations were validated against those shown on scanned copies of the topographic maps used during the original sampling program, where these were available. The possibility still exists that samples are located incorrectly despite this effort. Catchments were not generated in those cases where the location of a sample cannot be adequately verified. Consequently, the number of catchments included for a particular maps sheet may not equal the number of original field sites. CSA Global accepts no responsibility for the accuracy of sample locations or their derived catchments. The user is encouraged to undertake independent validation of any areas of interest derived from this work.

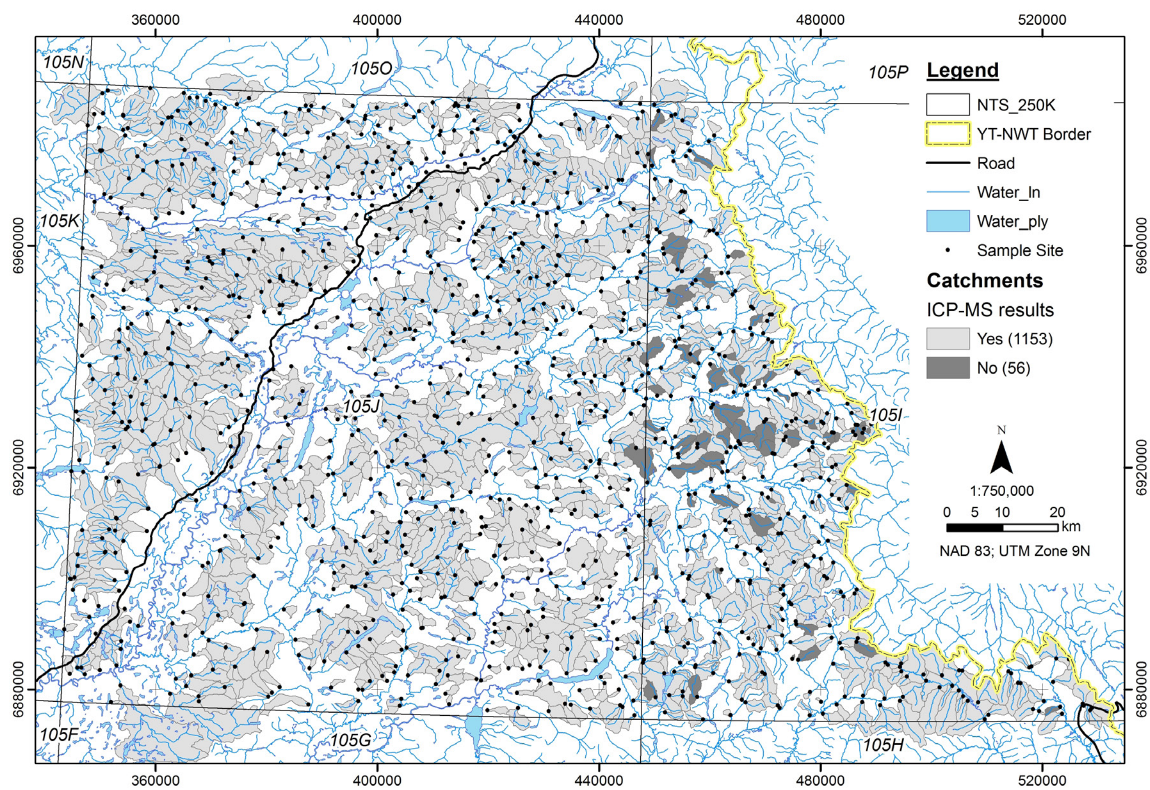

Figure 1. *Example of stream sediment sample locations and catchments for map sheets 105J and 105I.*

In order to assess the impact of varying geology on the stream sediment geochemistry, each sample has been attributed with the dominant underlying lithological unit for the associated catchment. For this study a new map product was generated by the YGS combining elements of both bedrock and surficial geology maps (Fig. 2). Second-order and greater derivatives of bedrock including fluvial/alluvial, glaciofluvial, glaciolacustrine, and organic deposits identified on the surficial geology maps were merged into a Q layer ("Exotic Quaternary"). These higher-derivative materials are typically well-mixed, can be far-travelled, and mask underlying bedrock. Bedrock polygons were then replaced where necessary by the "Q layer" to create the new geology map product. First derivative surficial sediments (glacial till/moraine, colluvium, weathered bedrock) are typically more representative of local bedrock, and thus were excluded from the Q layer. Given that catchment basins can extend outside the limits of the map sheet, the geology map used for the catchment query included information from parts of adjacent map sheets using a 15 or 20 km buffer. Because rock composition is the primary influence of stream sediment geochemistry, rather than stratigraphic relationship, a simplified legend was generated based on the Rock Subclass field of the YGS digital bedrock compilation map. The percentage of each material type within each catchment was calculated in ArcMap™ and each sample attributed with the dominant material type.

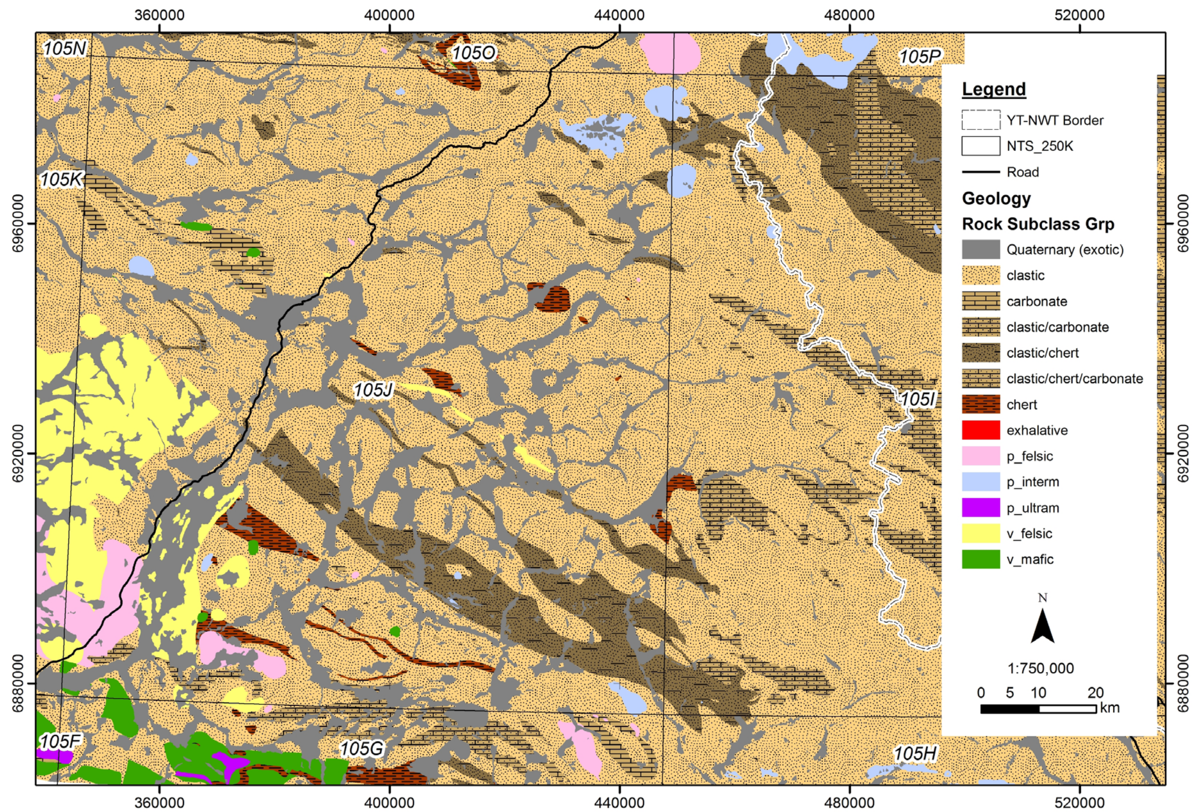

Figure 2. *Example of simplified geological units for map sheets 105J and 105I.*

The main controls on the observed chemical variation were constrained by exploratory data analysis ("EDA") in ioGAS™ geochemical assessment software utilizing various statistical approaches. Element associations are defined by principal component analyses using a correlation matrix following a centered-log ratio transformation to remove the effects of closure (Aitchison, 1986). This provides a statistically relevant means to assess the effects of scavenging of cations by secondary Fe and Mn-oxides, clays and/or organic material. Only samples with complete ICP analyses were included in the principal component analysis as the use of centred log ratios requires a complete multivariate data set. Box-plots were used to asses which elements are strongly controlled by changes in underlying geology. Spatial patterns of principal components were reviewed in relation to mapped geology to provide additional support for determining bedrock control. To correct for the effects of scavenging, elements that show strong correlations with Fe, Mn, Al or LOI underwent regression analysis. Similarly, elements that show a strong relationship to underlying geology underwent $\log_{10}$ Z-score levelling based on the dominant lithological unit mapped within each catchment (*e.g.*, Arne and Bluemel, 2011; Heberlein, 2013; Arne and Brown, 2015).

Weighted sums models were calculated for a variety of deposit types that exist, or are likely to exist, in the area based on a review of known mineral occurrences within the region (Yukon MINFILE 2015). Importance rankings were assigned based on published elemental associations from other districts (*e.g.*, Goodfellow, 2007; Hart, 2007; Paradis *et al.*, 2007; Peter *et al.*, 2007; Robert *et al.*, 2007; Taylor, 2007) but modified using an iterative approach based on EDA and validation against known occurrences. Furthermore, importance rankings also reflect the quality of the available data. For example, while it is tempting to rank Au high in a weighted sums model for Au deposits, Arne and MacFarlane (2014) have demonstrated the imprecise nature of historical RGS Au analyses from Yukon, and so the weightings used for Au have been somewhat moderated.

Weighted sums modeling (WSM) was completed using two approaches. The first approach used data derived from either levelling by dominant geology within a catchment, or residuals calculated from regression analysis to correct for scavenging (*e.g.*, Arne and Brown, 2015). For map sheets where ICP-MS data were not available for all samples the combined dataset was used. This approach assumes that the most aerially extensive map unit within a catchment is the primary control on the geochemistry of the stream sediment, which may not always be the case. For example, thin metal-bearing units such as black shales (which may or may not be a mappable unit) could have a disproportionately strong influence on the composition of the stream sediment, either due to their enriched metal content or relative ease of erodibility. Limited exposure of these horizons would also inhibit consistent mapping. The levelling procedure requires that for each geologic unit there should be at least 10 catchments in order to define reliable estimates of mean and standard deviation. This means that mapped lithological units were grouped prior to levelling. Local topographic changes within a catchment and the effects of variable weathering would likely also have an effect on the relative influence of different geologic units in the stream sediment geochemical data.

The second approach utilizing only the ICP dataset, uses principal component analysis (PCA), rather than mapped geology, to define key geochemical domains and filter their influence on the distribution of commodity and pathfinder elements. For example, the first principal component for many samples within the Selwyn basin often shows high loadings for Cd, Mo, Ag, Hg, Sb, Ba, Zn and V and forms a spatial trend that matches the distribution of the Road River Group which contains shale horizons that are likely to be elevated in these metals. The reader is referred to Grunsky (2010) for a general description of the use of PCA for the interpretation of geochemical survey data and Grunsky *et al.* (2014) for an example of the interpretation of soil geochemistry using this technique. Garrett and Grunsky (2001) also mention the use of principal components in weighted sums modeling.

In order to identify geochemical anomalies in multivariate space, regression analysis was completed using the principal component(s) that are interpreted to reflect metal-bearing lithological units. Commodity and pathfinder elements were regressed against the principal component(s) for which they had high positive or negative loadings. In most cases, regression analysis included one or two of the first four principal components. The calculated residuals were then used in the WSMs. Preliminary assessments indicate that the PCA approach more effectively removes the influence of varying geology and may therefore provide a better means of identifying mineralization.

WEIGHTED SUMS MODELING

The following provides a general description of the modeling procedure and results based on the assessment of the first several map sheets. Additional information, including a table showing the importance rankings used in the modeling for selected deposit types is presented on each individual map. Each model is optimized for a specific deposit type, although multiple deposit types may be represented in a given model due to similarities in elemental abundances and associations.

The variables used in the WSMs based on data levelled by dominant geology are either residuals calculated from regression analysis (*e.g.*, Co-Fe residuals), or Z-score values from levelling by dominant geology based on the results of EDA. The importance rankings were initially chosen depending on whether the variable represents a commodity or pathfinder element for a given deposit type. They were then adjusted iteratively by validating the results against the locations of known mineral occurrences. Based on the assessment of the first several map sheets, it was found that in some instances levelling certain pathfinder elements (*e.g.*, Cd, Ag, Mo) by dominant lithology did not fully subdue the effects of variable lithological background (*i.e.*, terrane effect). In order to reduce this effect, these elements were sometimes given low importance rankings, or in some cases were omitted all together. Negative rankings were used to help differentiate deposit types that have similar metal associations. For example, negative rankings for Pb and Zn are used in the WSM for epithermal Au-Ag in order to reduce the contribution of Ag related to SEDEX mineralization.

The variables used in the WSMs based on principal components are residuals calculated from regression analysis against selected principal components. As above, importance rankings were chosen to reflect the relative importance of the commodity and pathfinder elements based on validation against the locations of known occurrences. For the most part, the importance rankings for each variable are similar to those from the WSMs generated using levelled data. However, because the principal component method appears to be more effective at subduing terrane effects, higher importance rankings could be used for certain pathfinder elements. However, the strong responses in Zn, Pb, Ag related to SEDEX, for example, are sometimes still evident in the WSMs calculated using principal components and negative weightings for these elements were thus still required to distinguish them from other deposit types in some instances.

The effectiveness of the historical sampling coverage has been assessed empirically using graphs of WSMs plotted against catchment surface area to determine at what point the WSM values appear to fall away to regional background (*e.g.*, Arne and Bluemel, 2011; Heberlein, 2013; Arne and Brown, 2015). Catchments above this surface area are interpreted to have been under-sampled by the original survey and would benefit from a more detailed survey. These catchments represent new exploration opportunities. Those samples from catchments with areas greater than the maximum estimated for effective sampling that have anomalous WSM values are of particular interest because they contain values above regional background in spite of the potential for considerable dilution.

The WSMs are presented as maps with catchments thematically-coloured by weighted sums scores using percentile breaks. Two map products exist for each deposit type: one based on data levelled by dominant mapped geology, and the other based on principal component residuals. Catchments with surface areas greater than the maximum estimated for effective sampling are delineated with a heavier polygon outline so that the WSMs can be directly assessed with respect to effectiveness of the original sampling. Mineral occurrences are also shown on the map in order to judge the usefulness of the WSMs and to highlight catchments with high WSM scores where no occurrences have been documented.

Stream water pH from the original open file reports has been used to define a separate thematic map for this project. In general, stream water pH will reflect the lithological units exposed in the catchments, although this may be modified locally by the oxidation of sulphides exposed at or near surface. The pH of water draining each catchment, along with its Eh, will control the precipitation of Fe and Mn hydroxides that have the capacity to adsorb various metal ions and thus generate false geochemical anomalies. The potential for the hydromorphic accumulation of metals has been evaluated through the generation of map products in which WSMs are generated either through the use of levelled Fe, Mn and commonly scavenged metals, such as Co and As, or through plotting a principal component considered to represent the hydromorphic transport and precipitation of either Fe and/or Mn as well as associated metals. No hydromorphic maps have been produced for those map sheets in which the geochemical data show no evidence for possible scavenging effects. These are generally map areas dominated by high local relief.

CONCLUSION

Weighted sums models have been generated for various deposit types using two different approaches designed to subdue chemical variations related to changes in geology and enhance responses potentially related to mineralization. The models generated by the two approaches are considered to be complimentary and should be used in tandem. Preliminary assessments suggest that while levelling by mapped geology is an improvement over using raw data it appears that this approach may not fully filter interpreted 'terrane-effects' for certain map sheets. For some deposit types however, such as SEDEX Pb-Zn deposits, regionally anomalous values for certain elements (*e.g.*, Cd, Ba and Zn) could be indicative of a prospective horizon. In this case the models based on levelled data may be more effective in identifying prospective regions or distal expressions of certain deposit types. Conversely, in trying to identify anomalies outside of areas of high background the models using principal component residuals are preferred. Comparing the models for different deposit types can also provide important context. For example, elevated values in the porphyry Cu-Mo and polymetallic Ag-Pb-Zn models could represent proximal and distal environments of the same porphyry Cu mineral system. The models generated using residuals on principal components use only the ICP-MS data however and therefore, in some instances, provide less coverage than the models based on levelling a combination of historical and ICP-MS data. For some map sheets, WSM are generated for deposit types that have not yet been found in the region. Because these models cannot be validated against known occurrences the reader is encouraged to incorporate other datasets to assess overall prospectivity. It should also be borne in mind while reviewing the catchment maps accompanying this report that geochemical anomalies unrelated to known mineral occurrences may have several explanations, including the presence of un-recognized map units influencing catchment geology or incorrectly located samples, as well as the presence of near-surface mineralization.

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