Towards a Drainage Geochemical Atlas of British Columbia

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INTRODUCTION

Drainage geochemical surveys utilize a combination of water and stream or lake sediment media collection and chemical analysis for rapid and effective evaluation of mineral resources within fluvial catchment areas. Low-density surveys (typically at a density of one sample site per ~10 km^2) are a cost-effective method for regional mineral exploration covering thousands of square kilometres. Drainage geochemical surveys are based on the principal that the bedrock and surficial geology underlying the drainage catchment area upstream from a sample site will be reflected in the sediment chemistry. Background element variations in drainage sediment can characterize the source bedrock geochemistry and may outline metallogenic belts. Elevated metal contents may indicate mineralized bedrock or rock types that are the potential hosts of economic mineral deposits. However, low density (e.g., an average of one sample per 13 km^2 in British Columbia) sampling is not sufficient to detect all mineral deposits unless their surface exposure is substantial.

Internationally, regional surveys for geochemical mapping, metallogenic studies and mineral exploration have been carried out by governments and mining companies for over 30 years. Darnley (1990) reported on the beginning of an international geochemical mapping (IGM) project in 1988 that was sponsored by the International Union of Geological Sciences and UNESCO. Since then, there have been more examples of national mapping surveys from many countries, including the United Kingdom (Plant et al., 1989, 1997), Greenland (Steenfeld, 1993) and China (Xie and Ren, 1993). The results of national geochemical surveys are commonly displayed in the form of an atlas that shows the spatial distribution of elements as either symbol or contour maps. One of the first of these to be produced was the Wolfson *Geochemical Atlas of England and Wales* (Webb, 1978); since then, there have been several others, such as the *Geochemical Atlas of Alaska* (Weaver, 1983).

Much of British Columbia is a mountainous terrain with numerous rivers, an ideal physiography for the application of drainage geochemical mapping. Consequently, the BC Geological Survey started a regional stream sediment and stream water geochemical survey (RGS) in 1976 as part of the Geological Survey of Canada's National Geochemical Reconnaissance Program (NGR). Since its inception, 70% of the province has been surveyed, with the collection and multi-element analysis of more than 50 000 stream sediment, lake sediment and surface water samples at an average density of one sample per 13 km^2. Since 2006, Geoscience BC has contributed to the RGS database with information from stream and lake sediment geochemical surveys (e.g., Jackaman, 2006).

With the widespread use of personal computers, multi-element RGS data analysis and spatial analysis have been used to identify regions of high mineral potential. The data have also proven useful for establishing environmental baseline geochemistry.

Advantages of the RGS for geochemical mapping are that 1) few changes have been made to analytical and sample preparation methods since the start of the survey, and 2) strict quality control has been maintained during sample preparation and analysis. Thus, the data from all survey areas can be combined into a relatively seamless geochemical database. This paper reports on the first, comprehensive, province-wide, geochemical atlas products arising from the integration of this database through the use of GIS spatial analysis. The *Geochemical Atlas of British Columbia* (Lett et al., in press) is an ongoing project, with updates of the atlas anticipated as new data come available to augment the stream sediment, moss-mat sediment (moss sediment) and lake sediment results that are distributed over approximately 70% of the province, as shown in Figure 1.

SOURCE DATA

Information used to create the *Geochemical Atlas of British Columbia* has been extracted from the British Columbia Regional Geochemical Survey database, a Microsoft Access® database implemented in the late 1980s and most recently revised in 2007 for the BC Geological Survey's MapPlace portal. Among the database tables used for the atlas are the following:

RGS Sample Location Information: This table has a unique sample identification number that combines NTS map sheet, year and sample number. It also contains a code for the sample type (e.g., 1, stream sediment; 7, moss-mat sediment; 9, lake sediment), location co-ordinates (UTM Zone, northing and easting, datum used [i.e., NAD 83]) and a quality-control sample code identifying field replicate samples. There are presently 56 475 sample locations in the database.

RGS Field Stream Lake: This table has all of the field information for stream sediment, lake sediment and surface water samples. It includes such criteria as water colour, stream depth, stream width, bank composition and sediment texture.

RGS Routine Water: This table includes pH, F and U results from the analysis of surface stream and lake water. For

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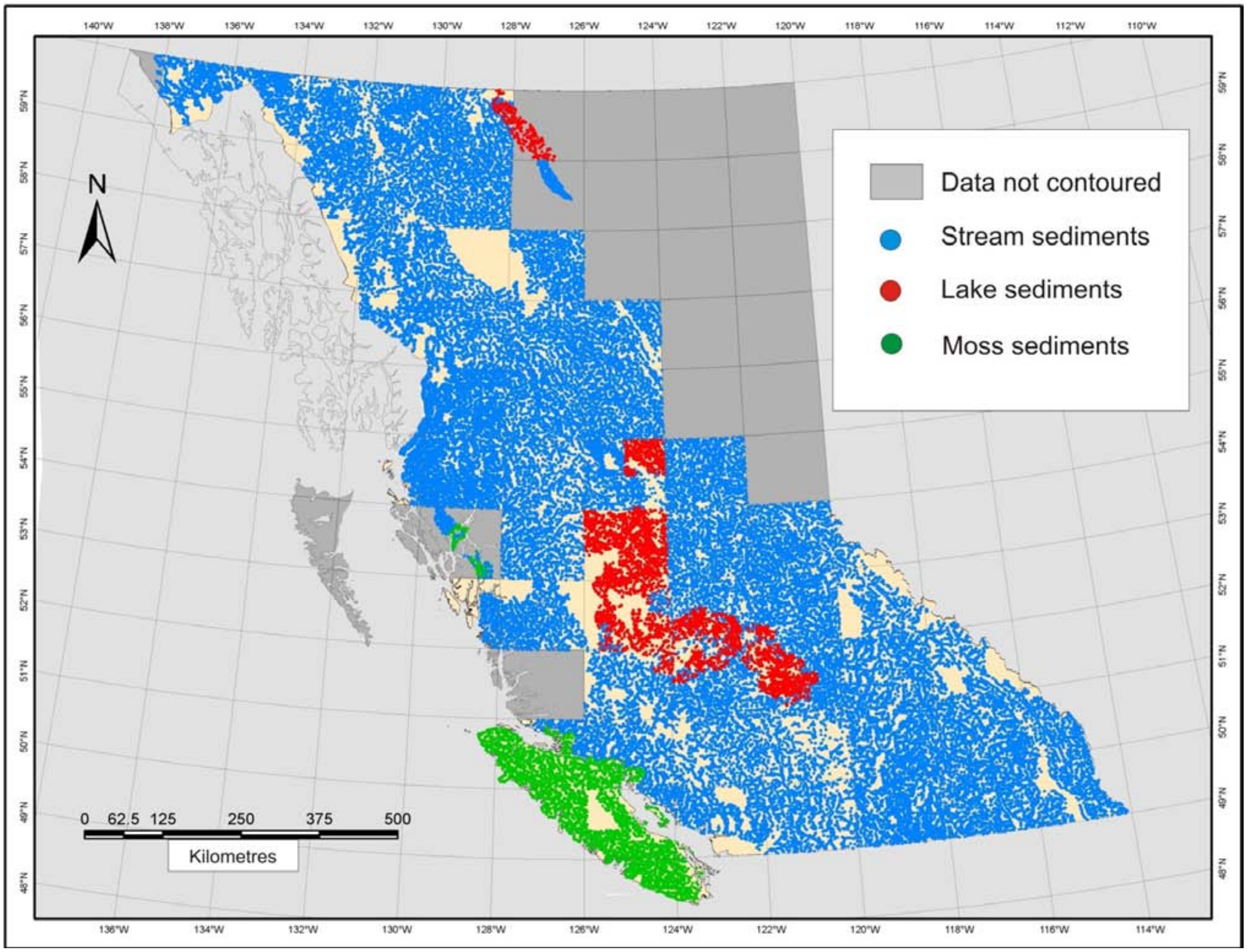

Figure 1. Distribution of stream sediment, moss-mat sediment (moss sediment) and lake sediment geochemical sample sites in British Columbia.

recent surveys (since 2002), water conductivity was also recorded.

RGS Stream Sediment AAS: This table comprises analytical data for stream sediment, moss-mat sediment and lake sediment analyzed by an aqua regia ($HCl-NHO_3$) digestion followed by atomic absorption spectrophotometry (AAS). The table also includes the results for samples analyzed for Au by lead-collection fire assay (FA) and AAS, and for loss-on-ignition at 500^{o}C.

RGS Stream Sediment ICP-MS: This table comprises analytical data for stream sediment, moss-mat sediment and lake sediment analyzed by an aqua regia ($HCl-NHO_3$) digestion followed by inductively coupled plasma – mass spectrometry (ICP-MS).

RGS Stream Sediment INAA: This table comprises analytical data for stream sediment, moss-mat sediment and lake sediment determined by instrumental neutron activation analysis (INAA).

Data Merging — Analytical Methods Comparison

The RGS database comprises analytical results for more than 70 elements determined by a combination of aqua regia – AAS, aqua regia – ICP-MS and INAA. However, province-wide coverage exists for only 40 of these elements and the data can be used to create maps showing their regional variation. Thirty of the elements are not considered because they are determined by a variety of methods that produce incompatible results. In addition, the data may be limited by high instrumental detection limit, interelement inferences or analysis of only a small number of samples for a particular element (e.g., Sn).

All of the samples have been analyzed for a core group of ore-indicator elements (e.g., Au, Cu, Co, Ni, Pb, Zn), but there exist differences in the detection limits for aqua regia – AAS and aqua regia – ICP-MS, as shown in Table 1. Samples from surveys prior to 1999 were analyzed by aqua regia – AAS, whereas those from more recent surveys were analyzed by aqua regia – ICP-MS, and there are few examples where drainage samples were analyzed by both methods. As a basis for comparison between these two main analytical techniques, 1152 stream sediments from the McLeod Lake regional survey that were initially analyzed by aqua regia – AAS were later reanalyzed by aqua regia – ICP-MS for up to 37 elements, including Cu (Lett and Bluemel, 2006). Near-perfect correlation between the two methods is shown for Cu in Figure 2, where the scatterplot

TABLE 1. INSTRUMENTAL DETECTION LIMITS FOR ELEMENTS DETERMINED BY AQUA REGIA – AAS AND AQUA REGIA – ICP-MS.

Element	Units	ICP-MS	AAS
Ag	ppb	2	100
Al	%	0.01	nd
As	ppm	0.1	1
Au*	ppb	0.2	nd
B	ppm	1	nd
Ba	ppm	0.5	nd
Bi	ppm	0.02	nd
Ca	%	0.01	nd
Cd	ppm	0.01	0.1
Co	ppm	0.1	2
Cr	ppm	0.5	nd
Cu	ppm	0.01	2
Fe	%	0.01	0.01
Ga	ppm	0.2	nd
Hg	ppb	5	5
K	%	0.01	nd
La	ppm	0.5	nd
Mg	%	0.01	nd
Mn	ppm	1	5
Mo	ppm	0.01	1
Na	%	0.001	nd
Ni	ppm	0.1	2
P	%	0.001	nd
Pb	ppm	0.01	2
S	%	0.02	nd
Sb	ppm	0.02	1
Sc	ppm	0.1	nd
Se	ppm	0.1	nd
Sr	ppm	0.5	nd
Te	ppm	0.02	nd
Th	ppm	0.1	nd
Ti	%	0.001	nd
Tl	ppm	0.02	nd
U	ppm	0.1	nd
V	ppm	2	5
W	ppm	0.2	nd
Zn	ppm	0.1	2

shows a strong linear relationship with a correlation coefficient of +0.957. Similar correlation between the original and reanalyzed results for other elements of the McLeod Lake survey, especially those that underwent essentially the same digestion method used since the start of the RGS program, justify the merger of AAS and ICP-MS analytical results into datasets for production of maps for the *Geochemical Atlas of British Columbia*. A modified form of exploration data analysis has been used to compare populations of data produced by different analytical techniques, because few samples from the broader RGS database have been reanalyzed by aqua regia – ICP-MS.

EXPLORATION DATA ANALYSIS

Exploration data analysis (EDA) is designed to detect trends or structures in geochemical data. It involves graphical and numerical techniques that are independent of assumptions about element distributions. In this way, EDA resolves problems related to the common failure that statistical assumptions have in describing real data, and the overwhelming influence that large populations have on smaller but often significant distributions (Kurzl, 1988). Box plots and Q-Q plots can also be used to compare geochemical data, such as subsets from the RGS database generated by different analytical methods and from different sample media. Pseudo – box plot divisions have been constructed from the following statistical ranges to compare datasets. The divisions are as follows:

Lower fence (Q1 – 1.5(Q3 – Q1)) — also known as interquartile range/whisker

First quartile 1

Median

Third quartile 3

Upper fence (Q3 + 1.5(Q3 – Q1)) — also known as interquartile range/whisker

Values above or below the fences are considered outliers

Based on the techniques described by Kurzl (1988) and Grunsky (2007), a pseudo – box plot approach has been applied to statistically examine the relationship between the results produced by the different analytical methods. An example of a pseudo – box plot for Cu by AAS and ICP-MS is shown in Figure 3. All of the box plots will accompany maps in the final *Geochemical Atlas of British Columbia* (Lett et al., in press). The graphs can be used to determine if the data need to be levelled with a correction factor so that misleading trends in plotted data are avoided. The first stage of the statistical analysis has been to calculate median, 1st quartile, 3rd quartile, and 'fence' values from Pb, Co, V, Fe, Mo, Hg, Sb, Cd, Bi, Zn and Cu results by AAS and ICP-MS. These statistics were plotted as a function of concentration on a simple line graph to produce a pseudo – box plot. In the same fashion, U by delayed neutron counting (NADNC) was compared to U by INAA, and Au by INAA was compared to the data produced by lead-collection fire assay – AAS. Arsenic results by AAS, ICP-MS and INAA were also compared, and the similarity be-

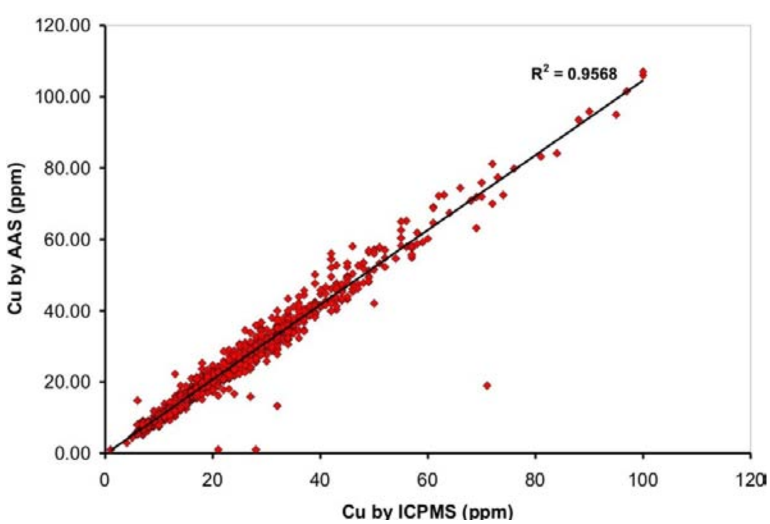

Figure 2. Scatterplot for 1152 stream sediment samples from the McLeod Lake map sheet (NTS 93J) initially analyzed for Cu by aqua regia – AAS and later reanalyzed for Cu by aqua regia – ICP-MS (Lett and Bluemel, 2006). Abbreviations: ppm Cu-AAS, Cu by AAS (ppm); ppm Cu-ICPMS, Cu by ICP-MS (ppm).

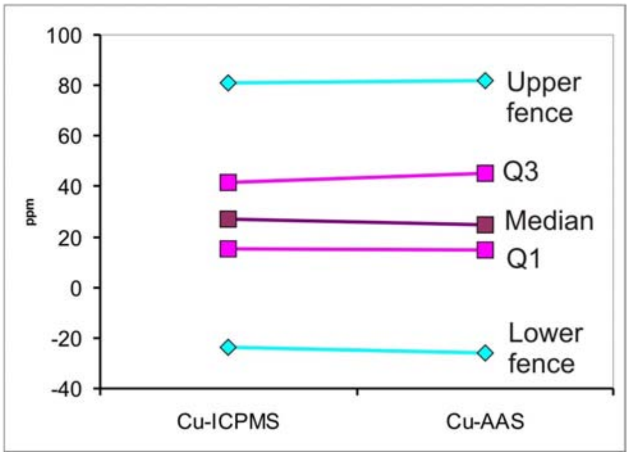

Figure 3. Pseudo – box plot comparing median, quartile and fence values for Cu by AAS and ICP-MS. The graph was prepared from 46 379 AAS determinations and 12 132 ICP-MS determinations. Q1 and Q3 are the 1st and 3rd quartiles, respectively. Abbreviations: Cu_ICPMS, Cu by ICP-MS; Cu_AAS, Cu by AAS.

tween results produced by all three methods justified merging the three datasets. This is the only case where INAA results were merged with aqua regia – ICP-MS/AAS results (Lett et al., in press).

Comparison of pseudo – box plots reveals that most RGS elements have almost identical median and quartile values for AAS, ICP-MS and INAA methods, indicating that no levelling is needed. Consequently, data from the following methods can be merged into a single file for map plotting:

Pb — AAS with ICP-MS
Co — AAS with ICP-MS
U — NADNC with INAA
V — AAS with ICP-MS
Au — FA with INAA
Fe — AAS with ICP-MS
Mo — AAS with ICP-MS
Mn — AAS with ICP-MS
Ni — AAS with ICP-MS
Hg — AAS with ICP-MS
As — AAS with ICP-MS or INAA
Sb — AAS with ICP-MS
Cd — AAS with ICP-MS
Bi — AAS with ICP-MS
Zn — AAS with ICP-MS
Cu — AAS with ICP-MS

DATA MERGING — SAMPLE MEDIA COMPARISON

Element data for stream sediment, moss-mat sediment and lake sediment were compared using pseudo – box plots in the same way that different analytical methods were treated. Data from the same analytical technique (e.g., aqua regia – AAS) were used to compare two different sample types, such as stream sediment and moss-mat sediment. An example of a pseudo – box plot for Cu in stream sediment

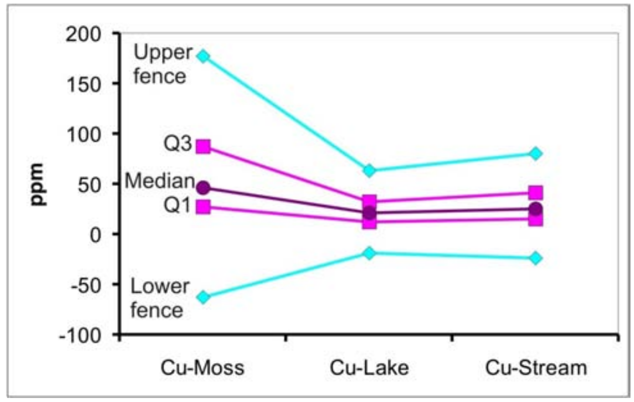

Figure 4. Pseudo – box plot comparing Cu in stream sediment (Cu_Stream) with Cu in moss-mat sediment (Cu_Moss) before levelling. Q1 and Q3 are the 1st and 3rd quartiles, respectively.

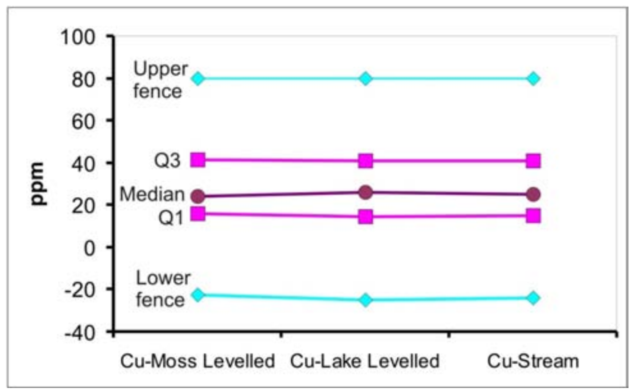

Figure 5. Pseudo – box plot comparing Cu in stream sediment (Cu_Stream Levelled) with Cu in moss-mat sediment (Cu_Moss Levelled) after levelling. Q1 and Q3 are the 1st and 3rd quartiles, respectively.

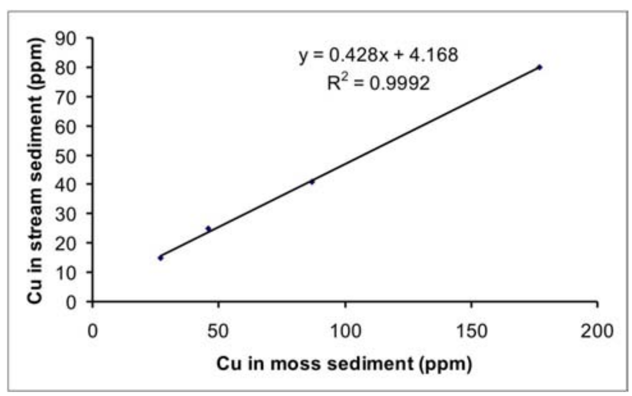

Figure 6. Example of a Q-Q plot for Cu in stream sediment and Cu in moss (moss-mat) sediment.

compared to lake sediment and moss (moss-mat) sediment is shown in Figure 4. Levelling of moss-mat sediment or lake sediment data to stream sediment data was carried out with Q-Q graphs, where the 1st quartile, 3rd quartile, median, lower fence and upper fence for each sample media dataset were plotted on a scatter graph. Least-squares best-

TABLE 2. LEVELLED AND UNLEVELLED CU AND NI VALUES FOR THE PERCENTILES USED FOR CONTOURING IN FIGURES 7, 8, AND 9. ABBREVIATIONS: L, LEVELLED; NL, UNLEVELLED.

Percen-tile	Cu NL (ppm)	Cu L (ppm)	Ni NL (ppm)	Ni L (ppm)
10	9	9	5	4.68
20	13	13	8	8
30	17	17	12	12
40	21	21	15	16
50	26	25	19	20
60	31	30	24	25
70	38	37	30	31
80	47	46	40	41
85	54	52	48	49
90	65	61	62	64
95	89	80	94	95
98	132	114	148	148
99	170	151	250	251

fit regression lines were generated (in the simple form, y = mx + b, where 'm' is the slope and 'b' is the intercept) and a common intercept ('b') was used to level the moss-mat sediment or lake sediment element values with stream sediment data. A pseudo – box plot is shown in Figure 5 and an example of a Q-Q plot for Cu is shown in Figure 6. Substituting the analyzed moss-mat and lake sediment values ('x') into the equation for stream sediment results in transformed data distributions with a least-squared best-fit regression line having a slope ('m') and intercept ('b') like that of stream sediment data distribution for the element of interest.

MAP PLOTTING

Of the 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 85th, 90th, 95th, 98th and 99th percentile values calculated from the raw and levelled data for each element, only those above the 50th percentile were used for plotting the atlas maps. The unlevelled and levelled Cu and Ni values that correspond to the percentiles shown on the maps are listed in Table 2. Percentiles for the levelled data were used as intervals for contours on the atlas maps. The maps were prepared using both ESRI ArcMap® 9.2 and Manifold System 8. Each program produces slightly different representations, but the same trends and patterns are maintained. Attribute tables for each element were queried and imported from Microsoft Access. Contours were created by kriging using the spatial analysis tool in each program. Output cell size

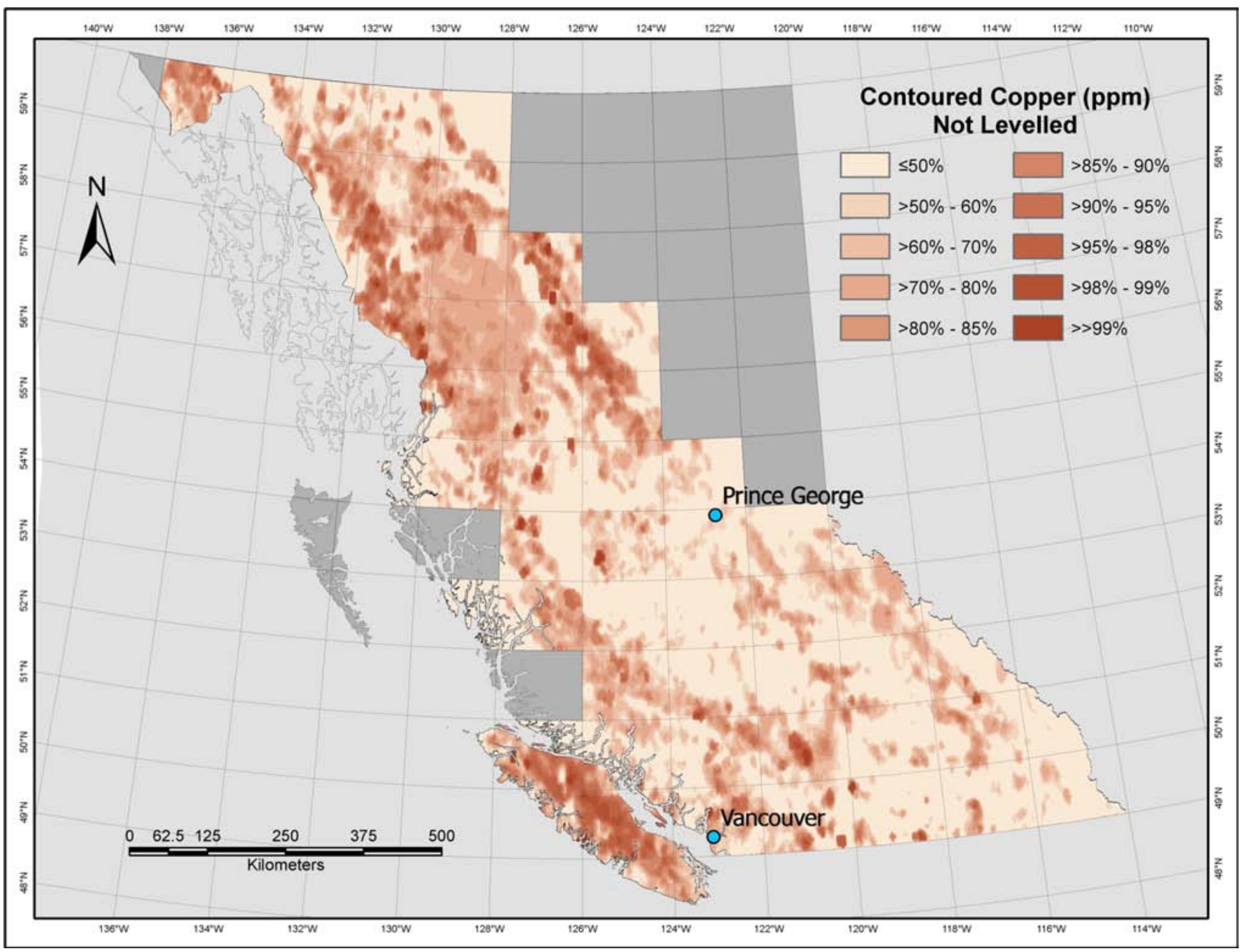

Figure 7. Contoured unlevelled Cu from merged AAS and ICP-MS stream sediment, lake sediment and moss (moss-mat) sediment data.

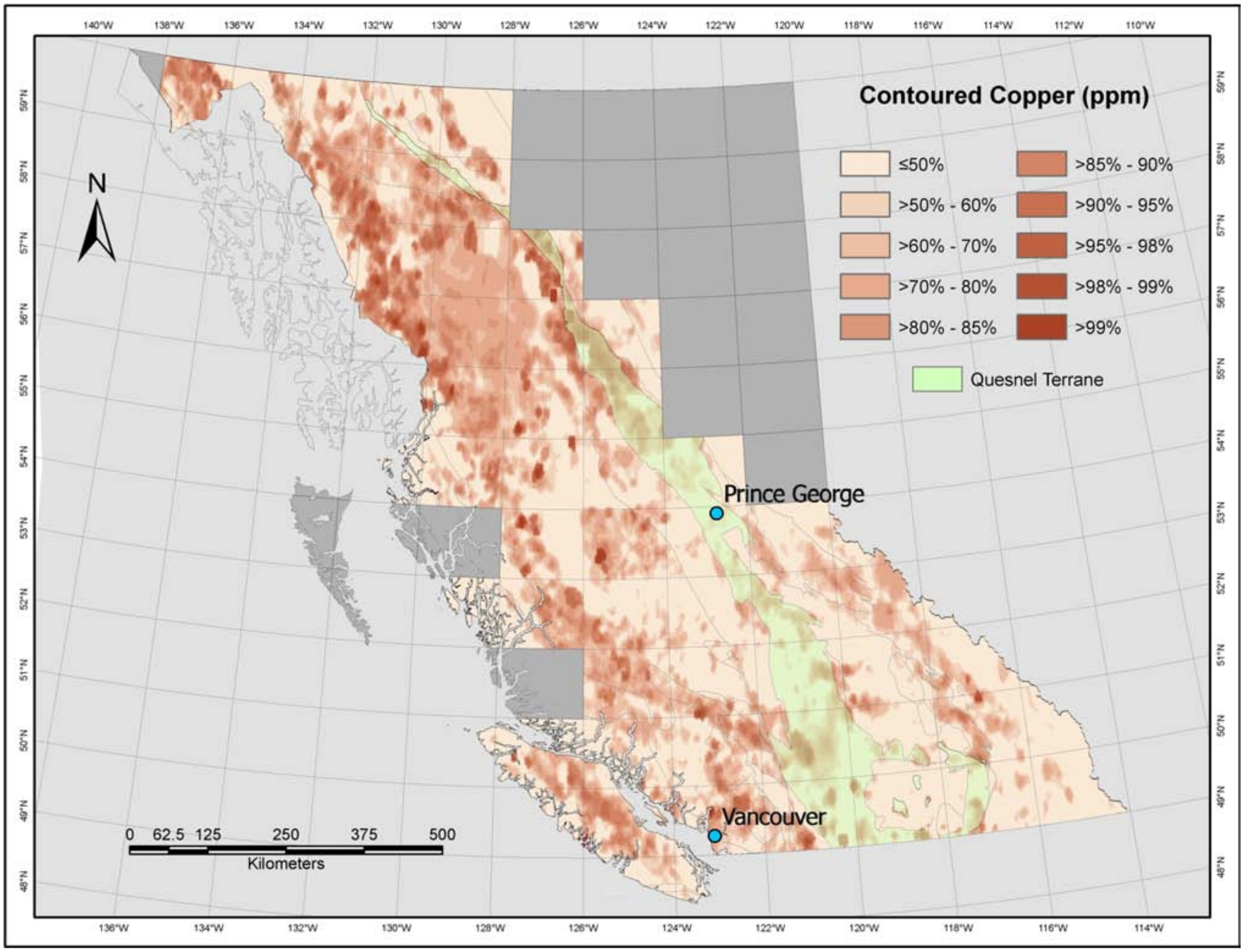

Figure 8. Contoured levelled Cu in stream sediment, lake sediment and moss-mat sediment, determined by combined AAS and ICP-MS.

was set to 0.05 of a degree, the search radius was set to 'program determined' and the number of neighbour points on which to base the prediction was set to 10. The resultant raster surface was combined with data from the digital geographic base map of British Columbia.

Contoured maps plotted from unlevelled and levelled Cu data are shown in Figures 7 and 8. Although the Cu trends are essentially the same in both contoured maps, there is an enhancement of Cu geochemistry in the unlevelled dataset (Fig 7) for some parts of British Columbia, such as Vancouver Island. This apparent enhancement reflects differences in the sample media, with higher Cu background in the moss-mat sediments that were collected mainly on Vancouver Island, compared to stream sediments collected in most other parts of the province. The levelled drainage sediment Cu data (Fig 8) reveal several belts where the elevated Cu shows a spatial relationship to geological terranes. For example, northwest-trending belts of elevated sediment Cu in central BC correspond to the volcanic island-arc sequences that form much of Quesnel Terrane. The outline of the Quesnel Terrane on the contoured Cu map is shown in Figure 8. Contoured Ni values in Figure 9 illustrate how this element can help outline metallogenic belts when the data are presented in an atlas format.

CONCLUSIONS

- Selected Pb, Co, V, Fe, Mo, Hg, Sb, Cd, Bi, Zn and Cu data for up to 56 000 reconnaissance-scale stream, lake and moss-mat drainage survey sediment samples have been compiled to form the basis for the *Geochemical Atlas of British Columbia*.
- Levelling methods have been applied to correct population differences arising from differences in analytical technique and/or sample media.
- To date, ESRI ArcMap® 9.2 and Manifold System 8 layouts for the atlas maps have been produced for selected elements. Data files and documentation that will constitute the first-generation atlas will be available as BC Ministry of Energy, Mines and Petroleum Resources GeoFile 2008-1 (Lett et al., in press).
- Future use of the geochemical atlas and derivative products will help to better define metallogenic belts with new mineral deposits.

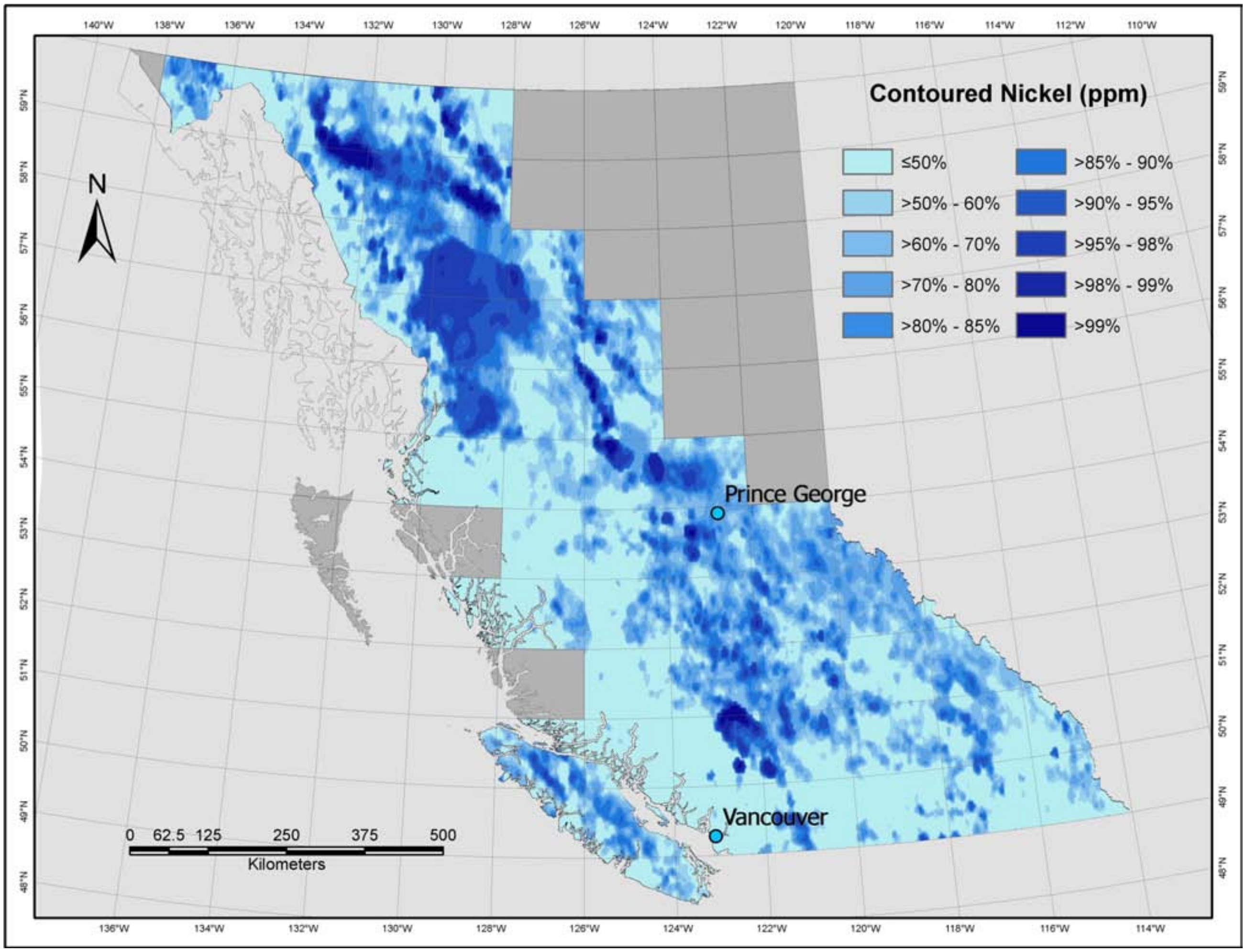

Figure 9. Contoured levelled Ni in stream sediment, lake sediment and moss-mat sediment determined by combined AAS and ICP-MS.

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