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TILL GEOCHEMISTRY OF THE MOUNT MILLIGAN AREA (PARTS OF 93N/1 AND 93O/4)

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TABLE OF CONTENTS

	Page
INTRODUCTION	
Introduction	1
Description of the Study Area	1
Regional Geology and Mineralization	2
Surficial Geology	3
METHODS	
Sample Collection	5
Sample Preparation and Analysis	5
Map Production and Data Handling	5
RESULTS AND DISCUSSION	
Data Quality	7
Concentration of Elements	7
Pathfinder Elements for Porphyry Copper-Gold Mineralization	7
Dispersal Length and Sampling Density	8
CONCLUSIONS	11
ACKNOWLEDGMENTS	11
REFERENCES	13

APPENDICES		*Page*
Appendix A	Analytical Data	A-1
Appendix B	Analytical Duplicate Data	B-1
Appendix C	Summary Statistics	C-1
Appendix D	Element Maps	D-1

TABLES

1. Analytical methods and detection limits for elements used in this study 5
2. Analytical and total precision for ten selected elements 7

FIGURES

1. Location of the Mount Milligan study area 2
2. Geology of the mount Milligan area. Modified from Nelson et.al.(1991) and Struik (1992). A more detailed map is provided in Appendix D. 2
3. Simplified surficial geology of the Mount Milligan area, from Kerr and Sibbick (1992) 3

INTRODUCTION

This open file contains data from a geochemical survey conducted in the vicinity of the Mount Milligan porphyry copper-gold deposit. The survey was undertaken to provide critical data for the design and interpretation of regional till surveys for porphyry copper-gold exploration. Sibbick and Kerr (1995) reported the summary results and exploration recommendations of this survey. Some of the results presented here are derived from that work. Additionally, this open file reports detailed results of the survey including element distribution maps, data listings and summary statistics. This study was conducted in conjunction with a biogeochemical survey of the same region (Dunn *et al.*, 1996).

The successful design and interpretation of a regional drift-exploration survey requires information regarding the geochemical response of the drift to the type of mineral deposit being sought. Key factors to determine include: the elements which reliably indicate the deposit type (pathfinder elements); residence sites of the pathfinder elements; and their characteristic style(s) of dispersal and dispersion. These factors can then be used to develop guidelines for selecting the most appropriate size fraction for analysis, sampling density and analytical techniques. Moreover, this information is essential for interpreting existing data, including pathfinder elements, their anomalous thresholds, and characteristic spatial patterns and length of dispersal trains.

Till is the preferred sample medium for regional geochemical drift-exploration surveys. As the *first derivative* of bedrock (Shilts, 1993), till represents comminuted bedrock debris or older surficial sediments entrained, transported and deposited by active glacial ice. Till, of all glacial sediments, most commonly reflects the composition of its source area. Further, although it may have undergone more than one glacial episode, its source can often be inferred to interpreted ice-flow patterns and history.

Porphyry-style mineralization is particularly suited to regional-scale till surveys, given the large size of the mineralization-alteration systems involved. The Interior Plateau of British Columbia has received considerable interest as an area of high mineral potential for porphyry-style mineralization. The Mount Milligan porphyry copper-gold deposit (MINFILE 093N 194) and surrounding region has attracted an array of geological, geochemical and geophysical studies by industry, government and university scientists. In addition to numerous industry exploration programs, these include bedrock mapping by Nelson *et al.* (1991) and Struik (1992), mineral deposit studies by DeLong *et al.* (1991), surficial geological mapping by Kerr (1991) and Plouffe (1991, 1992), geochemical studies by Gravel and Sibbick (1991) and Kerr and Sibbick (1992) and geophysical mapping by Shives and Holman (1992). Preliminary results of a regional till geochemical survey in the adjoining Manson River and Fort Fraser map areas (NTS 93K and 93N) were released by Plouffe and Ballantyne (1993).

DESCRIPTION OF THE STUDY AREA

The Mount Milligan study area, centered at latitude 55°07'N and longitude 124°00'W, is located approximately 150 kilometres northwest of Prince George in north-central British Columbia (Figure 1). The area is accessible by logging road from Fort St. James and from Windy Point on Highway 97. Access within the study area is limited. Exploration roads network the western third of the area near the Mount Milligan deposits, but access to the eastern two-thirds of the area is restricted to a few roads of limited extent.

Located on the Nechako Plateau, the study area is characterised by a relatively flat to hummocky plain at 1000 metres elevation, bounded on the west and east by north trending ridges of 1300 to 1500 metres elevation. Mount Milligan, 5 kilometres north of the Mount Milligan deposits, rises to an elevation of 1508 metres.

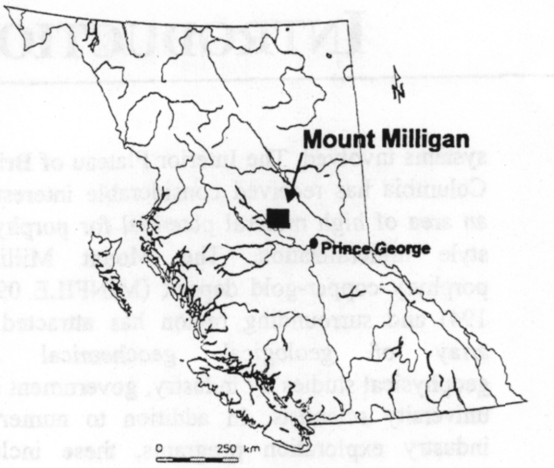

Figure 1. Location of the Mount Milligan study area.

REGIONAL GEOLOGY AND MINERALIZATION

Takla Group rocks of the Quesnel Terrane underlie the Mount Milligan area (Nelson *et al.*, 1991). The Quesnel Terrane is an early Mesozoic island-arc sequence bounded on the west by oceanic rocks of the Cache Creek Terrane and on the east by oceanic rocks of the Slide Mountain Terrane. Metamorphic rocks of the Wolverine Complex are also in contact with the eastern boundary of the Takla Group/Quesnel Terrane (Struik, 1992). Takla Group rocks consist of Upper Triassic volcanics, pyroclastics and epiclastic sediments. Numerous coeval plutons, up to early Jurassic age, intrude the Takla Group.

The Mount Milligan deposits (Figure 2) are centered on Early Jurassic crowded plagioclase-porphyritic monzonite intrusions known as the MBX and Southern Star stocks (Nelson *et al.*, 1991). These, and numerous smaller stocks, intrude Upper Triassic Takla Group augite (± plagioclase) porphyry agglomerate, trachyte breccias and flows, and bedded epiclastic sediments of the Witch Lake Formation. Directly east of the intrusions, a fault (known informally as the Great Eastern Fault) juxtaposes Takla Group rocks against Eocene continental sediments within an extensional basin (Nelson *et al.*, 1991). The eastern half of the study area is underlain by Witch Lake Formation, as well as basalt, diorite and locally limestone of the Philip Lakes succession (Struik, 1992). Quartzofeldspathic gneiss, schist and granite pegmatite of the Wolverine Metamorphic Complex outcrop in the east and northeast (Struik, 1992).

Alteration associated with the deposit comprises a crudely zoned potassic core centered on the intrusions (DeLong *et al.*, 1991), and surrounded by an east-west elongate 3.0 by 4.5 kilometre propylitic alteration halo. Mineralization consists primarily of disseminated and fracture-filling chalcopyrite and pyrite. Lesser quantities of bornite are present within the potassic alteration zone. Approximately 70% of the mineralization is hosted by the Witch Lake volcanics with the remaining 30% in the monzonite intrusives. Gold is associated with chalcopyrite, pyrite and bornite as small grains up to 100 µm in diameter along sulphide grain boundaries and microfractures in pyrite (Faulkner *et al.*, 1990). Both gold and chalcopyrite are associated with the potassic alteration zone (DeLong *et al.*, 1991). Reserves of the deposit are estimated at 298.4 million tonnes grading 0.45 gram per tonne gold and 0.22% copper (Schroeter, 1995).

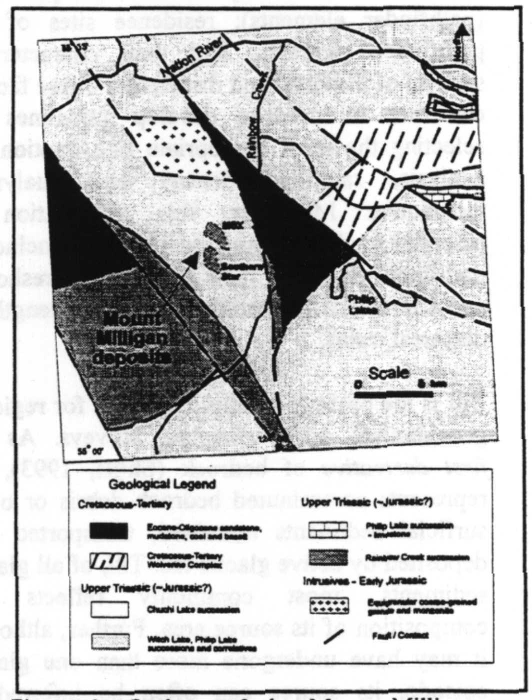

Figure 2. Geology of the Mount Milligan area. Modified from Nelson *et al.*, (1991) and Struik (1992). A more detailed map is provided in Appendix D, page D-2.

Subparallel polymetallic sulphide veins containing disseminated to massive pyrite and chalcopyrite, radiate outward from the MBX stock in the propylitic alteration zone. The best-developed veins are 0.3 to 3.0 metres thick and contain 3 to 100 grams per tonne gold, 0.2 to 10% copper, 1 to 3% sphalerite, and traces of arsenopyrite and galena (Faulkner *et al.*, 1990).

SURFICIAL GEOLOGY

The last glacial event in the Mount Milligan region occurred during the Late Wisconsinan (Fraser Glaciation) between 25 940±380 years B.P. and 10 100±90 years B.P. (Clague, 1981). Regional ice movement during this event was primarily to the northeast, as interpreted from ice-flow indicators such as well-developed striae scoured into bedrock and drumlinoid features developed in unconsolidated sediments. This observation of regional flow is in accordance with earlier studies by Armstrong (1949) to the north, west and south of the Milligan area, and more recently by Plouffe (1991, 1992) in the Stuart and Fraser lakes area to the southwest. In the McLeod Lake region to the southeast, Struik and Fuller (1988) mapped the extent of glacial lake deposits and noted the presence of mineralized clasts in morainal deposits.

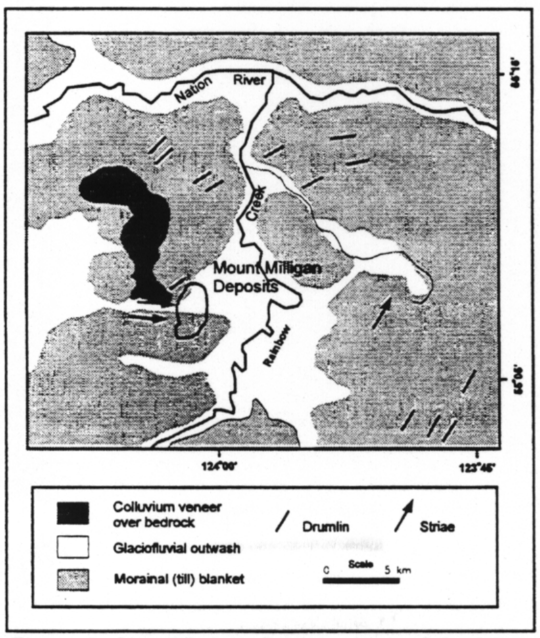

Figure 3. Simplified surficial geology of the Mount Milligan area, from Kerr and Sibbick (1992).

Surficial sediments of the study area include till, glaciofluvial and fluvial sand and gravel, glaciolacustrine sand, silt and clay, colluvium and organic materials (Kerr, 1991). Two surficial units predominate: an extensive morainal (till) blanket and large glaciofluvial outwash complexes (Figure 3). Till was deposited during the last glacial episode and is commonly hummocky and drumlinized. It consists of a dense matrix-supported diamicton composed of very poorly sorted, angular to well-rounded pebbles to cobbles in a sand-silt-clay matrix . (Kerr and Sibbick, 1992). These sediments are more continuous in the east half of the map area, from south of Philip Lakes to north of Nation River. Flow was towards the northeast during full glacial conditions. South of Nation River, a gradual change in flow direction towards the east is indicated by drumlinoid features.

Glaciofluvial sand and gravel dominate the central part of the study area along the axis of Rainbow Creek, Nation River valley to the north and to the west of the Mount Milligan deposits (Kerr and Sibbick, 1992). These outwash-sediment complexes consist of sinuous esker ridges up to 10 kilometres long, kame deposits and a series of broad overlapping outwash fans deposited by glacial meltwater during ice retreat. They represent the end product of a long period of glacial and fluvial erosion, transportation and reworking of many types of surficial sediments. Within the narrow Nation River valley, glaciofluvial sediments are locally overlain by up to 20 metres of glaciolacustrine silt and clay. These sediments were deposited during ice retreat in a glacial lake with an elevation of approximately 850 metres (Kerr and Bobrowsky, 1991). Colluvial sediments derived from till and weathered bedrock form a veneer over steep hillsides and valley walls in the highlands north and south of the Mount Milligan deposit. Highlands to the northeast of the Philip Lakes are also mantled by colluvial sediment.

Drift thickness is highly variable, ranging from less than 1 metre on rocky highlands to over 80 metres in the Rainbow Creek area (Kerr and Sibbick, 1992). Thicknesses in excess of 100 metres are common directly east of the Mount Milligan deposits (Kerr and Bobrowsky, 1991). Ronning (1989) has reported overburden depths in excess of 200 metres in the Nation Lakes area to the west.

Humo-ferric podzols are the main soil type of the region. Modifications of the original till substrate by soil-forming processes extend to an average depth of approximately 0.5 metre. Oxidation of the parent materials generally extends to a depth of 2 metres.

METHODS

SAMPLE COLLECTION

Till samples were collected down-ice from the Mount Milligan deposits for a distance of 20 kilometres to the east-northeast (Figure 2). A total of 121 till samples, including field duplicates, were collected from 108 hand-dug pits within a 150 square kilometre area. Sample sites are shown on page D-2, Appendix D. Sampling was concentrated in two distinct areas where till is the predominant surficial sediment: in the vicinity of the deposits, and in the region east of Rainbow Creek. The intervening area, consisting of glaciofluvial outwash, was not sampled, in order to maintain media consistency. Samples were collected on a 1 kilometre grid spacing. Additional sites were sampled in the vicinity of the deposits where exposures of till are more prevalent. The oxidized C-horizon was preferentially sampled at depths of 0.5 to 1.5 metres. Field samples weighed from 2 to 5 kilograms. Samples were partially air dried in the field and sent to the British Columbia Geological Survey Branch Analytical Sciences Laboratory in Victoria for further processing.

SAMPLE PREPARATION AND ANALYSIS

At the laboratory, the samples were removed from their plastic bags and thoroughly air dried at room temperature. Each sample was coned and quartered to obtain a representative subsample which was then dry-sieved to obtain the silt-clay (-62.5 μm) fraction. This fraction was further split to acquire representative analytical subsamples. Instrumental neutron activation analysis (INAA) for thirty elements was performed on 4 to 7 gram subsamples, and 0.5 gram sub-samples were analysed for thirty elements by inductively coupled plasma emission spectroscopy (ICP-ES) on an aqua regia digestion. Table 1 lists the analytical methods and detection limits for the elements discussed in this study. Analytical values below the reported detection limits are quoted as a value equal to the detection limit.

TABLE 1
ANALYTICAL METHODS AND DETECTION LIMITS FOR ELEMENTS USED IN THIS STUDY
(Detection limits in ppm unless noted)

Element	Method	D.L.
Aluminum	ICP	0.01%
Antimony	INAA	0.1
Arsenic	INAA	0.5
Barium	INAA	50
Calcium	ICP	0.01%
Cerium	INAA	3
Chromium	INAA	5
Cobalt	INAA	1
Copper	ICP	1
Europium	INAA	0.2
Gold	INAA	2 ppb
Iron	INAA	0.01%
Lanthanum	INAA	0.5
Lead	ICP	2
Lutetium	INAA	0.05
Magnesium	ICP	0.01%
Manganese	ICP	1
Neodymium	INAA	5
Nickel	ICP	1
Potassium	ICP	0.01%
Rubidium	INAA	5
Samarium	INAA	0.1
Sodium	ICP	0.01%
Thorium	INAA	0.2
Uranium	INAA	0.5
Vanadium	ICP	2
Ytterbium	INAA	0.2
Zinc	ICP	1

MAP PRODUCTION AND DATA HANDLING

The proportional dot maps for this open file are all plotted using the Universal Transverse Mercator projection (NAD27 datum), with a central meridian of 123° (Zone 10). The hydrography bases (NTS 93N and 93O) for the symbol maps were obtained in digital form from Surveys, Mapping and Remote Sensing Sector (SMRSS) of the Department of Natural Resources, Canada. The digital hydrography base was produced by splicing together the two 1:250 000 digital bases and then clipping the appropriate sub-area. The index map was also obtained from SMRSS and is presented using a Lambert Conformal Conic projection, Clarke 1866 spheroid, central meridian 95°, and standard parallels of 49° and 77°.

The geological base map is a compilation of those published by Nelson *et al.* (1991) and Struik (1992). The base was manually digitized and then transformed into the appropriate projection. Spatial point-in-polygon operations were then used to extract rock unit information for the individual sample sites. The rock unit attribute data were used in preparing the statistical summaries.

Map and symbol plots in this open file were produced using Unix-based ESRI ARC/INFO software. Computations were performed on UNIX workstations, with output to a 600 dpi Hewlett-Packard Laserjet printer. Analytical values for a particular element greater than or equal to the 98th percentile were plotted at the maximum symbol size; values less than the 98th percentile were scaled according to the user defined exponent. Exponents for individual elements were chosen to provide the best view of the analytical data. Accordingly, care should be exercised when attempting to compare elements plotted with different exponents.

RESULTS AND DISCUSSION

DATA QUALITY

Data quality was determined using duplicate field samples (13 pairs) and analytical duplicates (6 pairs). Precision was determined by calculating the average precision of a group of duplicate pairs for each element and size fraction. However, the limited number of duplicate pairs reduces the reliability of the precision estimates. Table 2 shows the total and analytical precision of ten elements. These elements were selected as potential pathfinders and for mineralization and lithologic variation (Sibbick and Kerr, 1995). Total precision (the sum of field and analytical variation) for each element is reasonable, ranging from 21% for iron to 116% for gold. Expectedly, analytical precision is less than the total precision for most elements, varying from 5% (manganese) to 184% (gold). Not surprisingly, the %RSD for gold is high, due to the occurrence of gold within the sample matrix as rare, discrete grains, resulting in the 'nugget effect' (Harris, 1982). Gold particles up to 100 μm in diameter are reported from the Mount Milligan deposits (Faulkner *et al.*, 1990). To provide a representative analysis of a sample containing gold grains of this size, analytical subsample sizes weighing 100 to 1000 grams are required, depending on the concentration of gold in the sample and the size fraction analysed (Clifton *et al.*, 1969). Sample weights used for gold analysis in this study (4 to 7 gram) are not considered representative. Use of larger sample sizes or the analysis of heavy minerals from the two coarse fractions are possible methods of improving the reproducibility of the gold analyses. However, the presence of anomalous gold concentrations can be considered a reasonable indication of the presence of anomalous gold within the till. Background concentrations of gold, however, should not exclude the possibility that anomalous gold concentrations are present.

CONCENTRATION OF ELEMENTS

Twenty-eight elements were selected for study (Al, Sb, As, Ba, Ca, Ce, Cr, Co, Cu, Eu, Au, Fe, La, Pb, Lu, Mg, Mn, Nd, Ni, K, Rb, Sm, Na, Th, U, V, Yb, and Zn). Elements excluded from this study had an excess of values at or below analytical detection limits. Summary statistics for the selected elements are listed in Appendix B.

TABLE 2
ANALYTICAL AND TOTAL PRECISION FOR TEN SELECTED ELEMENTS
(Precision estimated at 95% confidence level and expressed as percent relative standard deviation)

	Precision (%RSD)	
Element	Analytical	Total
Cu	11.8	42.1
Au	183.8	116.3
As	14.7	38.9
Sb	8.6	31.8
K	27.4	38.0
Fe	9.5	21.6
Mn	5.0	46.0
Ni	7.9	27.9
Co	13.3	24.3
Cr	9.3	30.1

PATHFINDER ELEMENTS FOR PORPHYRY COPPER-GOLD MINERALIZATION

Sibbick and Kerr (1995) utilized probability plots, proportional symbol maps and cluster analysis to determine which elements were pathfinders for porphyry copper-gold mineralization. Those elements not included as pathfinders showed either unimodal distributions or higher concentrations in the eastern half of the study area underlain by Wolverine Complex metamorphic rocks.

Elements found in anomalous concentrations in the vicinity of the Mount Milligan deposits included copper, gold, arsenic, antimony, potassium, cobalt, iron, manganese and chromium. Copper, arsenic, antimony and iron are anomalous above the Southern Star zone. Anomalous potassium values are found overlying the MBX zone but not over the Southern Star zone. Anomalous chromium values are present along the southern edge of the Southern Star zone and above the MBX zone.

Further analysis of the data showed that copper, gold, arsenic, antimony and potassium are pathfinders for the Mount Milligan deposits (Sibbick and Kerr, 1995). The mineralogy of the deposit suggests that anomalous concentrations of copper and gold originate primarily from the porphyry deposit, whereas anomalous arsenic and antimony are probably derived from polymetallic veins, such as the Esker vein, peripheral to the porphyry mineralization. Anomalous iron concentrations are a product of both the porphyry/vein mineralization and the extensive pyrite halo surrounding the deposit. The remaining elements (cobalt, manganese and chromium) reflect secondary weathering processes or variations in source lithology. Weak, but significant associations between potassium and the pathfinder elements are apparent. DeLong *et al.* (1991) observed a direct correlation between bedrock concentrations of copper and gold and the intensity of potassic alteration in the deposit. The weak association of potassium with the other pathfinders reflects the difference in mineral phases hosting copper, gold, arsenic, antimony (sulphides) and potassium (silicates) and the analytical methods used. Aqua regia incompletely decomposes silicates (*e.g.* potassium feldspar), whereas sulphides are almost completely dissolved. Instrumental neutron activation analysis, used for the determination of gold, arsenic and antimony, provides total element concentrations. Therefore, potassium determinations are only partial concentrations, whereas copper, gold, arsenic and antimony values represent total concentrations. Clays, which contain significant amounts of potassium, are more readily decomposed by aqua regia than silicate phases such as feldspar. It is possible that the source of potassium anomalies associated with the deposit originates from potassic or propylitically altered bedrock weathered to produce clays more amenable to digestion by aqua regia.

DISPERSAL LENGTH AND SAMPLING DENSITY

Estimation of dispersal distances from the Mount Milligan deposits is complicated by the presence of a wide band of glaciofluvial sediment, 3 to 5 kilometres wide, infilling the valley of Rainbow Creek. A broad zone of anomalous multi-element concentrations centered over the Mount Milligan deposits is approximately 3 by 3 kilometres in size. A cluster of elevated and/or anomalous concentrations of arsenic and antimony occurs up to 15 kilometres northeast (down-ice) from the deposit. However, the patterns exhibited by these elements east of Rainbow Creek suggest that they reflect local lithological differences (*e.g.* Witch Lake versus Wolverine Complex) and not down-ice dispersal from Mount Milligan.

Northeast of Philip Lakes, anomalous and/or elevated concentrations of copper form an east-west elongate pattern perpendicular to ice-flow direction. Similar patterns, albeit less well defined, are also observed for arsenic and potassium. Elevated concentrations of gold and antimony are not evident except at a single site. Mineralized boulders and limited exposures of sheared, altered and weakly mineralized volcanic rocks have been reported along the north shore of Philip Lakes (Cooke, 1989; 1991). Struik (1992) has mapped a northwest-trending fault (Philip Fault) which parallels the north shore of Philip Lakes (Figure 2), to which the mineralization is probably related. It is likely that the east-west elongate pattern of elevated element concentrations results from the glacial dispersal of altered or mineralized bedrock localized along this fault. Background concentrations in till samples from adjacent to the eastern arm of Philip Lakes imply that these samples are up-ice of the fault zone (see map, page D-11, Appendix D). Using this as a limit to the up-ice extent of mineralization, a maximum dispersal distance of 2 to 4 kilometres can be estimated for this area, based on element distribution patterns

Dispersal distances of up to 4 kilometres place constraints on the necessary sampling density required to detect the Mount Milligan deposits. Sinclair (1975) has demonstrated that to maximize the detection of elliptical anomalies (such as ribbon or fan-shaped anomalies in till) a sampling density corresponding to $\sqrt{2}/2$ times the length and width of the anomaly is required. Assuming an anomaly width of 3 kilometres (the width of the Mount Milligan anomaly) and a dispersal length of 4 kilometres, till samples collected on a 2.8 by 1.4-kilometre grid (long axis parallel to ice-flow direction) should intersect dispersal trains from porphyry mineralization similar in surface expression to the Mount Milligan deposits. Changes in the alignment of the grid, resulting from variations in ice-flow direction, could be eliminated by reducing the grid spacing to 1.4 by 1.4 kilometres. Higher sampling densities would be required to ensure detection of dispersal trains from porphyry mineralization with a smaller surface (or subsurface) expression. Lower sampling densities could be employed, but the probability of detecting mineralization would decrease.

CONCLUSIONS

CONCLUSIONS

Based on the results of this orientation survey, the following conclusions regarding the till geochemistry of the Mount Milligan area and recommendations for regional till geochemical exploration surveys for porphyry copper-gold mineralization may be made:

- Pathfinder elements for the Mount Milligan deposits include copper, gold, arsenic, antimony and potassium. Iron may also be a suitable indicator of pyrite alteration halos often associated with mineral deposits of this type
- Dispersal lengths of up to 4 kilometres from the deposits are observed. Longer dispersal distances, on the order of 10 to 15 kilometres, are not readily apparent.
- Sampling densities for regional till surveys of 1 sample per 2 square kilometres (1.4 by 1.4 kilometre grid spacing) are recommended for porphyry copper-gold exploration.

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