

Comparative Study of Partial and Selective Extractions of Soils over Blind Porphyry Copper-Gold Mineralization at Kwanika and Mount Milligan, Central British Columbia (NTS 093N/01, /19): Fieldwork, Soil Conductivity and pH Results

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Introduction

Exploration geochemistry in British Columbia has up to now relied on traditional methods, such as stream sediment and soil geochemistry, to detect metals dispersed mechanically and hydromorphically from outcropping sources. These methods have proven to be highly effective and there has been a long and impressive history of discoveries using them. As exploration maturity increases, however, mining companies are faced with the challenge of exploring more and more in areas of transported cover where traditional geochemical methods are less effective. Much of the central interior of British Columbia is covered by an extensive blanket of glacially derived sediments that completely masks the underlying bedrock. In order to deal with this cover, government, industry and academic institutions have invested heavily in developing airborne and ground geophysical methods to see through the exotic overburden. Unfortunately, geochemical exploration has not evolved as rapidly, despite the availability of a wide range of partial and selective extractions provided by the commercial laboratories. Reasons for this are varied and range from a general lack of understanding by the exploration community of the use and interpretation of these methods to scepticism about their effectiveness. It is only through well documented, nonbiased, comparative field testing of these methods that the exploration community can gain the knowledge and confidence to apply deep-penetrating geochemistry (DPG) to routine exploration programs.

There are relatively few examples of comprehensive comparative studies of DPG methods in BC. Cook and Dunn (2007) evaluated a number of partial leach methods over the 3T's epithermal Au-Ag prospect. They showed that B-horizon soils were more suitable than C-horizon tills for detailed geochemical sampling. Of the methods tested, they

concluded that Mobile Metal Ion (MMI[®]) and Enzyme LeachSM produced superior contrast responses to conventional aqua-regia digestion, although the latter method did detect mineralization in areas of thin cover. Lett and Sandwith (2008) carried out soil orientation surveys to test the effectiveness of a variety of selective and partial extraction methods at the Mouse Mountain, Shilo Lake and Soda Creek properties in the area of the cities of Quesnel and Williams Lake. Their study found that the most anomalous Cu and Au values, reflecting blind Cu-Au mineralization, occur in the C and lower B horizons with an aqua-regia digestion. A discussion of the performance of the various partial and selective extraction methods is still in preparation at the time of writing.

Outside of BC, there have been a number of important studies of DPG in a variety of climatic and physiographic environments. Perhaps the landmark study has been the Deep Penetrating Geochemistry Project, carried out by the Canadian Mining Industry Research Organization (CAMIRO). This study was funded by 26 mining companies, the Ontario Geological Survey and Geological Survey of Canada. Phase I considered movements of elements and ions from buried mineral deposits and nuclear waste facilities in arid and semi-arid environments. It showed that metals and ions can be transported to the surface by advective transport in gases and ground waters (Cameron, 1998; Cameron et al., 2002) and can be effectively detected by partial-extraction methods. In Phase II, a variety of test sites in arid, semi-arid and temperate boreal forest environments were studied. It was found that in all environments partial- and selective-extraction anomalies were detected in soils above buried mineralization (Cameron et al., 2004) and in some cases through appreciable thickness of complex transported cover.

The current study builds upon these important contributions by examining the effectiveness of a variety of partial and selective extractions over two blind porphyry Cu-Au deposits in north-central BC: the Central zone at Kwanika and the MBX-66 zone area at Mount Milligan (Figure 1). Both of these deposits subcrop beneath Quaternary glacial outwash deposits and at least part of the Kwanika Central

Keywords: *deep-penetrating geochemistry, Kwanika, Mount Milligan, copper-gold porphyry, soils, partial extraction, selective extraction, soil pH, conductivity*

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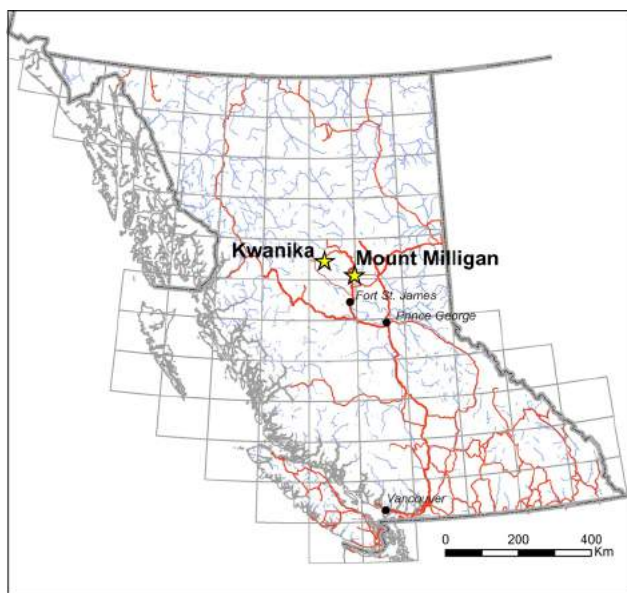


Figure 1. Location of study areas, central British Columbia.

zone lies beneath a post-mineral sedimentary basin. Kwanika is the site of a relatively pristine pine and spruce forest environment while at Mount Milligan the surface has been heavily disturbed by clear-cut logging and drilling activities. These contrasting environments provide a good test for the different methods.

This report documents fieldwork carried out at Kwanika and Mount Milligan projects between August 10 and 21, 2009. It also examines the preliminary results of soil pH and conductivity tests on soil samples from both projects. Results from partial and selective extractions will be the subject of a subsequent report as the analytical results are pending at the time of writing.

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Benefits to the Mining Industry

Independent, nonbiased studies of commercially available partial and selective extractions are few and far between, particularly in BC. These studies are important as they provide the exploration community with valuable insight into the appropriate sampling strategy and combination of analytical methods for a given environment. Without this type of study, the exploration geologist must rely on information provided by the commercial laboratories, who promote their own methods to see through transported cover. Without knowledge of the relative performance of these methods in different cover environments and for different deposit types, the exploration geologist could choose an inappropriate method on the basis of a laboratory's market-

ing rather than on sound scientific knowledge. This could be an expensive mistake. While all of the methods tested in this study have their merits, it is important to recognize that none of them can be used blindly in all environments. One size does not fit all. This study and others that have preceded it (Cook and Dunn, 2007; Lett and Sandwith, 2008) provide the exploration geologist with the knowledge and tools necessary to make an informed decision and therefore to maximize the benefit of their investment in geochemistry.

Another benefit of this type of study is that it gives mining companies a set of exploration tools and knowledge that helps improve their success rate for exploration projects in covered areas. Deep-penetrating geochemical methods can be used to effectively prioritize drillhole locations to test geophysical targets. Geochemical data can provide an additional layer of information to help discriminate potentially mineralized and barren targets. This reduces drilling risk and protects shareholder value.

Study Areas

Kwanika (Serengeti Resources Inc.)

The Kwanika project is situated in the Omineca Mining Division, approximately 140 km northwest of Fort St. James (55°30'N, 125°18'W; Figure 1). It is accessible by well-maintained Forest Service roads from Fort St. James via the community of Takla Landing. Serengeti Resources Inc., the owner, holds the title to 28 contiguous mineral claims covering an area of 8960 ha (Rennie and Scott, 2009).

The Kwanika Central zone is one of two mineralized centres located at the northern end of the Kwanika property. Together with the Southern zone, it forms a linear, north-trending, Cu-Au porphyry system hosted in several small monzonite intrusions along the western margin of the multiphase Hogem batholith (Rennie and Scott, 2009). Monzonite intrudes diorite, quartz monzonite and granite of the Hogem batholith as well as andesitic volcanic rocks of the Upper Triassic Takla Group. Intrusive and volcanic hostrocks are truncated to the west by the Pinchi fault: a major terrain boundary juxtaposing Cache Creek Terrane rocks to the west.

Mineralization at the Central zone is associated with a strong core of intense, texturally destructive albite alteration associated with a variable multiphase stockwork of quartz veinlets. Surrounding the albitic core is a broad zone of weak to strong, pervasive and fracture-controlled potassic alteration characterized by K-feldspar and secondary biotite (Rennie and Scott, 2009). This alteration grades laterally into propylitic assemblages. Dominant sulphide minerals include pyrite, which is ubiquitous to the deposit, chalcopyrite and bornite. Molybdenite is also commonly present. Supergene enrichment consisting of an upper ox-

ide zone with native copper and a lower sulphide zone with secondary chalcocite occurs on the upper surface of the hypogene mineralization beneath a package of younger conglomerate and sandstone that buries the mineralization to the west. These sedimentary rocks are interpreted to be part of a younger sedimentary basin formed against the Pinchi fault. The eastern part of the deposit subcrops beneath the Quaternary cover.

Surficial Environment

The Kwanika Central zone lies in a broad, flat-bottomed valley containing an extensive cover of glacial till and outwash sediments. Local elevations range from 900 to 1200 m but in the study area itself there is only 40 m of relief. Drilling has shown that the cover varies in thickness from a few metres to over 50 m thick in the immediate deposit area (D. Moore, pers. comm., 2009). Outcrops are rare and only seen in the bottom of the Kwanika Creek valley, which is deeply incised into the Quaternary sequence (Rennie and Scott, 2009). Away from the river valley, the surface is well drained with gently sloping topography. The area is forested with a mixture of lodgepole pine and white spruce as dominant species.

Three types of soil profile are present in the Central zone area. These are for the most part developed on a parent material of cobble-rich sand and gravel. Podzols (Orthic Ferro-Humic; soil nomenclature based on the Canadian System of Soil Classification [Canada Soil Survey Committee, Subcommittee on Soil Classification, 1978]) are the most widespread soil type, occurring on well drained, gen-

tle slopes within the pine and spruce forest. A typical profile (Figure 2) includes a thin LFH horizon consisting of partially decomposed wood, twigs, needles and mosses and a thin (<1 cm) black to dark brown, organic-rich Ah horizon. The organic-rich layers overlie a distinct white to grey or pinkish, sandy textured Ae or Ae_j horizon of variable thickness. Below this, the B horizon is made up of an upper B_f horizon (upper B), enriched with iron oxide, and a lower, medium to chocolate brown, BC horizon (lower B), which grades into medium to dark grey sand or gravel of the C horizon. Brunisols, the second soil type, are common at the base of slopes that are adjacent to boggy areas (Figure 3). A typical example has a surficial LFH and Ah horizon up to 4 cm thick overlying an undifferentiated olive-brown B_m horizon. The third soil type is represented by Organic soils. These occur in depressions and boggy areas (Figure 4). Profiles consist of an upper thick, peaty Om horizon that can be tens of centimetres thick, overlying a lower grey or blue-grey C horizon. A mottled B_g horizon was noted at one locality. In all cases, the lower part of the profile is water saturated.

Mount Milligan (Terrane Metals Corp.)

Mount Milligan lies about 100 km east-southeast of Kwanika. It is situated in the Omineca Mining Division, approximately 155 km northwest of Prince George and 95 km west of Mackenzie (55°7.35'N, 124°1.50'W; Figure 1). The principal access is by all-weather Forest Service roads from Mackenzie or by a longer and less maintained logging road from Fort St. James. The property, which is owned by



Figure 2. Typical Podzol profile from the Kwanika Central zone, British Columbia.

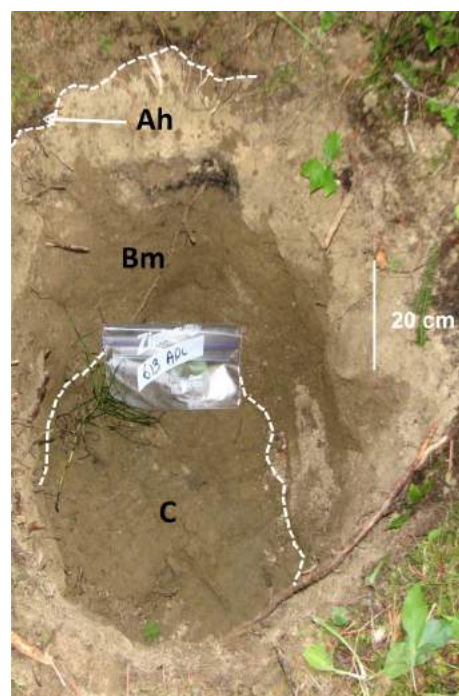


Figure 3. Brunisol from the Kwanika Central zone area, British Columbia.



Figure 4. Organic soil from the Kwanika Central zone area, British Columbia.

Terrane Metals Corp., includes 80 contiguous mineral claims that cover Upper Triassic Takla Group volcanic rocks and associated intrusions that form part of the highly prospective Quesnel Terrane.

There are three known porphyry Cu-Au deposits on the property: the MBX, 66 zone and Southern Star, which together constitute a resource (measured and indicated) of 590.8 million tonnes at 0.193% Cu and 0.352 g/t Au (Mills, 2008). The deposits are classified as belonging to the alkalic suite of porphyry deposits (Panteleyev, 1995). The principal mineralized body is the MBX–66 zone, which lies along the footwall of the west-dipping MBX stock and along the crosscutting Rainbow dike (Figure 5). The gold-dominant 66 zone is distinguished from MBX by higher Au:Cu ratios but, for all intents and purposes, the two deposits are part of a single mineralized system, which is the subject of this study.

Hypogene mineralization at MBX is dominated by chalcocyanite with lesser bornite and magnetite, associated with intense potassic alteration in the footwall of the stock and adjacent volcanic rocks. In contrast, mineralization at the gold-rich 66 zone occurs with intense albitization and abundant pyrite (Mills, 2008).

Surficial Environment

The MBX and 66 zone lie on the eastern slopes of a northwest-trending ridge of hills, which rises 300–500 m above the elevation of the surrounding plains. The highest point at 1508 m is the summit of Mount Milligan itself, which lies at the northwestern end of the ridge. Drainage patterns along the ridge are dendritic, becoming anastomosing on the surrounding plains where glacially fed, short, meandering streams connect pothole lakes, ponds and swamps (Gravel and Sibbick, 1991). In the vicinity of the mineral deposits, the ridge is divided by a steeply incised east-west valley occupied by Heidi lake, which drains east into King Richard creek (Figure 5).

Quaternary geology mapping by Kerr and Bobrowsky (1991) and Ricker (1991) identified a variety of surficial sediments in the study area (Figure 5). Colluvium derived from tills and bedrock dominates the flanks of the hills to the north and west of the MBX–66 zone area.

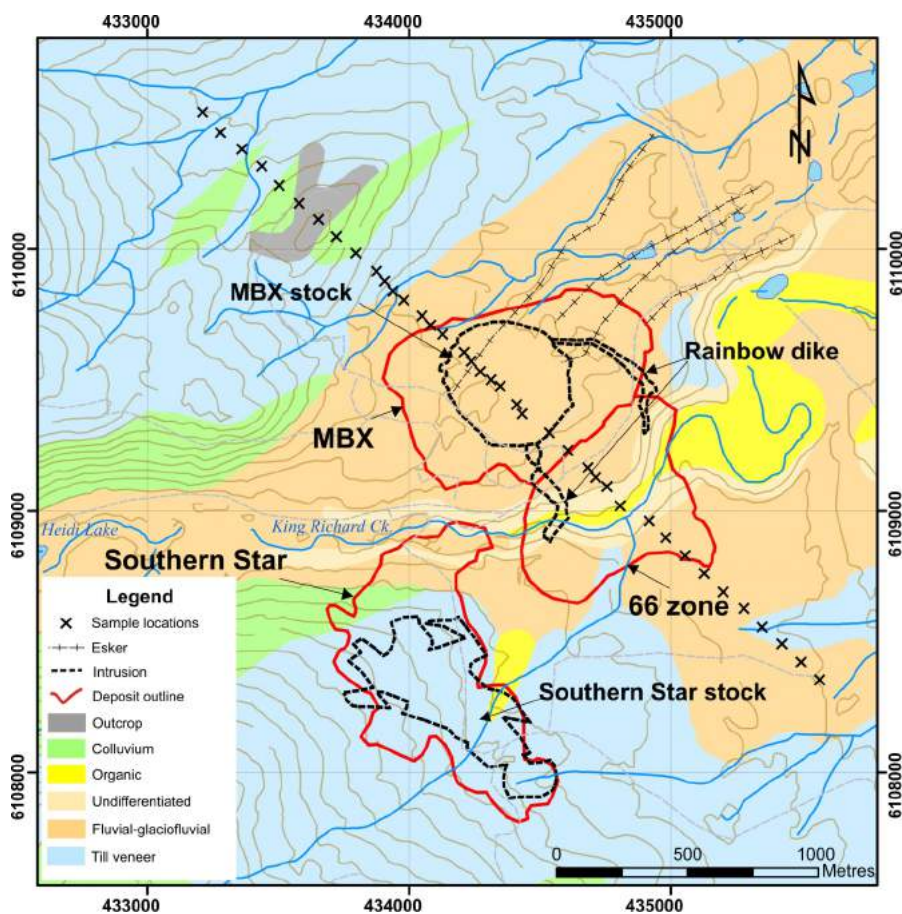


Figure 5. Mount Milligan, study area, British Columbia: sample transect, surficial geology and mineralized intrusions (modified after Ricker, 1991).

Away from the hills, the landscape is blanketed by a veneer of glacial till, which is overlain by a highly variable and complex sequence of glaciofluvial sand and gravel containing cobble- and boulder-rich layers. These deposits form a fan-like feature originating at Heidi lake and spreading out over the MBX-66 zone area to the east (Figure 5). Drilling has shown that the cover thickness is extremely variable, suggesting significant paleotopographic relief (Kerr and Bobrowsky, 1991).

Soils developed on the glaciofluvial deposits are dominantly Orthic Humo-Ferric Podzols. They typically have a thin organic layer made up of a 1–2 cm thick LFH horizon composed of partially decomposed twigs, needles and moss, which overlies a thin, poorly developed, Ah horizon of irregular thickness (0.5–2 cm). The organic-rich layers sit on top of a sandy textured, white, grey or pinkish eluviated Ae horizon or Ae_j horizon (a thin, discontinuous or barely discernible eluviated [Ae] horizon), which may vary from absent to over 10 cm in thickness. A strongly illuviated, red-orange, iron-rich Bf horizon is commonly found beneath the Ae horizon and in some places exceeds 15 cm in thickness. This horizon tends to have a fine silty texture. Bf horizon grades downwards over a few centimetres into a medium to olive brown Bm (an undifferentiated, uniform-coloured B horizon) or transitional BC horizon. Depth to the C horizon may vary from 25 cm over colluvium to 70 cm over sand and gravel. A typical Podzol profile is illustrated in Figure 6.

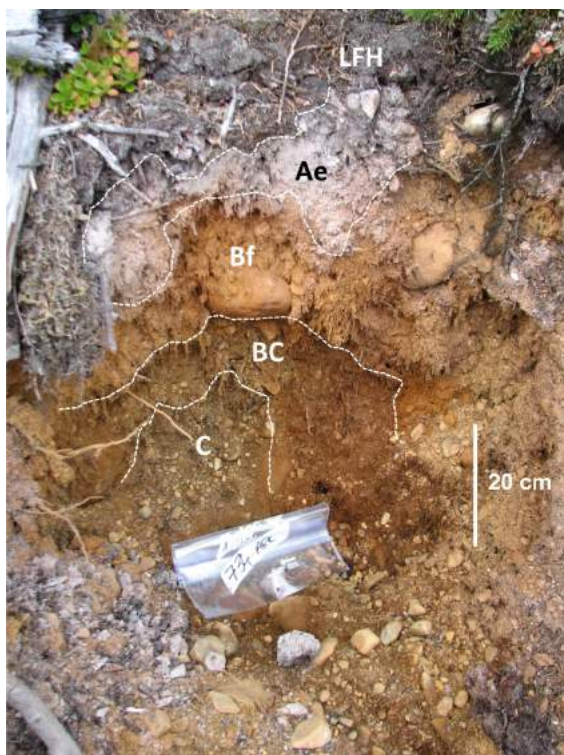


Figure 6. Typical Podzol profile developed on glaciofluvial sediments, Mount Milligan, British Columbia.

Widespread surface disturbance from drill access roads, drill pads and logging activities has resulted in either complete destruction or burial of the original soil profile over large parts of the MBX-66 zone area. Site selection for soil sampling is therefore very important. Where possible, remnant patches of the original surface were identified by the presence of original tree species (white spruce or lodgepole pine). In areas where the profile has been buried, holes were excavated to the original surface or moved to the closest possible location where the original profile is preserved.

As much of the area was clear-cut logged in the 1980s, original tree species are restricted to small enclaves between disturbed areas, water courses or steep slopes. White spruce and lodgepole pine are the dominant species on the well drained flats east of Heidi lake. In the creek valleys, black spruce, balsam poplar and trembling aspen are common. In the clear-cut areas, vegetation is dominated by pioneer shrub species like mountain alder and willow, which form dense thickets between the drill roads.

Sampling and Analyses

There has been much debate in the literature about the appropriate sampling strategy for partial- and selective-extraction geochemistry. Bradshaw et al. (1974) pointed out that “the depth of sampling during a soil program may be very critical as variations with depth can be greater than a factor of 10 within six inches”. A fixed depth interval (10–25 cm below the top of the mineral soil [Mann et al., 1998]), regardless of soil horizon, is recommended by SGS Mineral Services, the purveyor of the MMI leach. Their empirical observations from numerous field studies suggest that the zone of ion accumulation in the soil is a result of equilibrium between capillary rise and evaporation drawing ions upwards and downward leaching by percolating rainwater. Hamilton et al. (2007) conclude that consistent sampling is absolutely necessary for successful selective-extraction geochemical surveys and recommend a strategy of sampling between depths of 10 and 25 cm in mineral soil and below 30 cm in thick organic soil or peat.

Traditional soil sampling in BC has almost exclusively used the –80 mesh fraction of the B horizon. B horizon has been a favoured sampling medium because of the common presence of an illuviated iron- and manganese-oxide-rich Bf horizon that contains elevated metal contents compared to the other parts of the profile (Bradshaw, 1975; Levinson, 1974). It has proven to be an effective sampling medium in residual soil environments.

This study aims to test both the constant depth sampling strategy, with MMI extraction of upper B-horizon soils, as well as horizon-based sampling. Uniform soil profile development over much of the study area means that the upper B horizon occurs at a more or less consistent depth of be-

tween 5 and 15 cm. Upper B horizon samples were collected consistently from this interval.

Sample locations were accurately located using a Garmin GPSMAP® 60CSx handheld GPS receiver. At each site a 50 by 50 cm hole was excavated down to the C horizon to expose the complete soil profile. Each hole was photographed and described using a geochemical coding form and codes proposed by Hoffman (1986), along with the details of the immediate area.

Samples from the Ah, upper B, lower B and C horizons were screened to -12 mesh at the sample site to remove coarse fragments and roots. Where soil moisture precluded screening, coarse fragments were manually removed from the sample. Approximately 500 g of material was placed in 12.7 by 25.4 cm (5 by 10 in.) Hubco Inc. polyester-weave sample bags. Material from the top centimetre of the Ae horizon was tested for soil pH and conductivity. These samples and those for MMI extraction were collected in heavy-duty, polyvinyl chloride (PVC) Ziploc® bags.

Samples were analyzed by a range of proprietary and non-proprietary, selective and partial extractions, as well as by fire assay and super trace (an ALS Chemex proprietary method) for Au. The analytical methods and sampling horizons are summarized in Table 1.

Quality Control

Quality control (QC) measures used in this study include the collection of two types of field duplicates. In each survey area, five sites (about 10%) were randomly selected for field duplicate sampling. Two types of duplicates were col-

lected at these sites: within-hole and between-hole duplicates. Within-hole duplicates are a repetition of the original sampling procedure, collecting another soil sample from the cleaned walls of the soil pit. Between-hole duplicates are taken from a second hole dug as close to the original as possible, usually within 2 m. All duplicate samples were submitted blind to the laboratory.

No standard reference materials were used in this study. The reason for this is the unavailability of suitable matrix-matched materials that are certified for the methods being tested. In order to monitor and mitigate analytical drift, the samples were randomized prior to submission to the laboratory. Randomization has the benefit of distributing the effects of instrumental drift randomly throughout the sample population. It also allows for drift monitoring by plotting the samples in analytical order.

In addition to the field QC procedures, a number of steps were taken at the laboratories to ensure the quality of the analytical results. These include the introduction of analytical standards, blanks and lab duplicates into the sample stream.

Field Analyses

Soil pH

There is a growing body of evidence to indicate that variations in soil pH, or hydrogen ion (H^+) concentration, occur at the surface over buried sulphide mineralization. Smee (1983) proposed a mechanism, based on laboratory experiments and field tests, for the formation of metal anomalies in soils developed on glaciolacustrine clay over massive sulphides in the Abitibi Belt, northern Quebec. His work

showed that H^+ released as a byproduct of sulphide oxidation at the water table diffuses to the surface to form detectable acidic anomalies, and that pH sensitive elements like Ca, Sr, Mg, Fe and Mn in a boreal forest environment (i.e., slightly oxidizing to reducing) become redistributed in response to the pH shift.

Smee (1997, 1998) proposed a similar model for ion transport and indirect anomaly formation for arid environments. Results from a multicompany sponsored orientation survey at the Marigold gold deposit in Nevada (Smee, 1998) showed that Ca concentration, in all weak leaches tested, displayed a distinctive rabbit-ear or double-peak response with the peaks occurring over the edges of the mineralization. The ratio of weak leach Ca (e.g., acetic acid or hydroxylamine

Table 1. Sample media and analytical methods, Kwanika and Mount Milligan, British Columbia.

	Soil horizon	Ah	Ae	Upper B	Lower B	C	Other
Analytical method							
Sodium pyrophosphate		X					
Field pH/conductivity			X**				
Aqua-regia digestion		X		X	X	X	
Cold aqua-regia digestion				X			
Hot hydroxylamine HCl				X			
Cold hydroxylamine HCl				X			
De-ionized water				X			
Ionic Leach				X			
Bioleach				X			
Enzyme Leach SM				X			
Soil Gas Hydrocarbons SM				X			
Super trace gold				X			
Loss-on-ignition		X					
Mobile Metal Ion®-multielement							X*

* Sampled at constant depth typically from lower part of upper B and upper part of lower B horizons.

** Sampled from top centimetre of Ae horizon or top of mineral soil (Bf or Bm horizon depending on the profile type).

HCl) to aqua-regia digested Ca showed clear residual anomalies with the same rabbit-ear form and proposed that two forms of Ca exist in the soil; one of which is easily soluble and spatially related to mineralization and a second less soluble form, which represents background carbonate. Smee (1999) concludes that near-surface Ca over oxidizing mineralization is being remobilized in response to the upward movement of H^+ . Reprecipitation of Ca (carbonate) occurs where pH conditions permit, in other words over the edges of the sulphide body.

More recent work by Hamilton et al. (2004a, b) at the Marsh zone gold prospect and the Cross Lake volcanogenic massive sulphide (VMS) prospect in Ontario shows that similar rabbit-ear patterns occur in H^+ at the surface, above the edges of mineralization. They conclude that pH correlates with oxidation-reduction potential (ORP) and propose that H^+ production is a function of the redox conditions in the overburden column. In an earlier paper, Hamilton (1998) proposed the existence of reduced columns or chimneys in the overburden column above a reduced metal source. Reduction of the overburden column is postulated to occur as a result of upward migration of reduced anionic species between the top of a conductive body and the ground surface. Charge is transferred by the reaction with oxidized cationic species migrating in the other direction. This process results in the formation of an oxidation front that propagates to the surface to form a chimney or column. Within the reduced core of the chimney, oxidation of the underlying mineralization is inhibited thus limiting the amount of H^+ released. At the edges, however, oxidation is enhanced thus promoting H^+ accumulation at the surface over the edges of the underlying mineralization. This process results in a typical rabbit-ear response for H^+ , with a pronounced central low over the reduced chimney, from samples collected at the very top of the mineral soil profile.

The presence of similar patterns in the vastly different environments of Nevada (arid to semi-arid) and northern Ontario (saturated, boreal forest) suggest that a common process is operating in both environments. Regardless of the mechanism, H^+ accumulations (direct response) and redistributed near-surface carbonate (indirect response) should be easily detectable in the field using a simple pH meter and acid bottle. By taking two pH measurements of a 1:1 soil slurry (one without acid and a second with acid), the near-surface H^+ variation and the reactivity of the soil can be readily mapped. In addition to rabbit-ear H^+ peaks over the edges of the mineralization, the remobilized carbonate halo can also be identified. A simple plot of the inverse of the difference between the acidified and non-acidified H^+ concentrations (IDH; Smee, 2009) will highlight the zones of carbonate reprecipitation over the edges of the underlying sulphide body.

Soil Conductivity

Soil conductivity (EC), expressed as micro Siemens per centimetre ($\mu S/cm$), is a useful measurement in exploration geochemistry as it provides an estimation of the soluble anions and cations present in the soil. It has been suggested by various workers (Govett, 1974, 1976; Smee, 1998) that EC variations in surface soils reflect the release of salts and other ionic species as a result of the oxidation of sulphides at depth. Smee (1983) proposed that a special relationship between pH and EC may occur where ions have been mobilized and reprecipitated in response to a change in pH. Therefore a measurement of EC in soils over a sulphide body should show anomalous readings over the flanks of sulphide mineralization. Hamilton (1998) asserts that surficial geochemical anomalies, both rabbit-ear and apical, form above bedrock conductors as a result of strong redox gradients between the top of the conductor and ground surface; a reduced chimney. His model predicts the accumulation of ions at the edges of the reduced chimney as a result of anion movement up and out, and cation movement down and along redox gradients. These zones of ion accumulation should be readily detectable as areas of anomalous soil conductivity.

Results

This section describes the results of the field soil EC and pH measurements carried out at Kwanika and Mount Milligan. Results from the selective and partial extractions will be the subject of a follow-up paper.

Data Quality

Table 2 shows the results of the field duplicate samples for the soil pH and conductivity measurements, expressed as average percent relative standard deviations or RSD%. RSD% values for the pH and acidified pH are below 10% indicating that the results are highly reproducible. It is interesting to note that the RSD% values for the between-hole duplicates are actually slightly lower than for the within-hole duplicates. The reason for this is unclear. These results show that there is little variation in the soil pH values over distances of a few metres from a sample site.

Conductivity measurements have a higher uncertainty than the pH measurements with RSD% values ranging from 18.77 to 32.72%. Once again the between-hole values are marginally lower than those from the same hole; an observation that is not easily explained.

Table 2. Average percent relative standard deviations (RSD%) for field duplicates, Kwanika and Mount Milligan, British Columbia.

	Kwanika			Mount Milligan		
	Acidified			Acidified		
	pH	pH	Conductivity	pH	pH	Conductivity
Within hole	9.24%	2.97%	32.72%	4.62%	5.69%	23.71%
Between hole	7.10%	2.82%	18.77%	4.31%	3.09%	19.85%

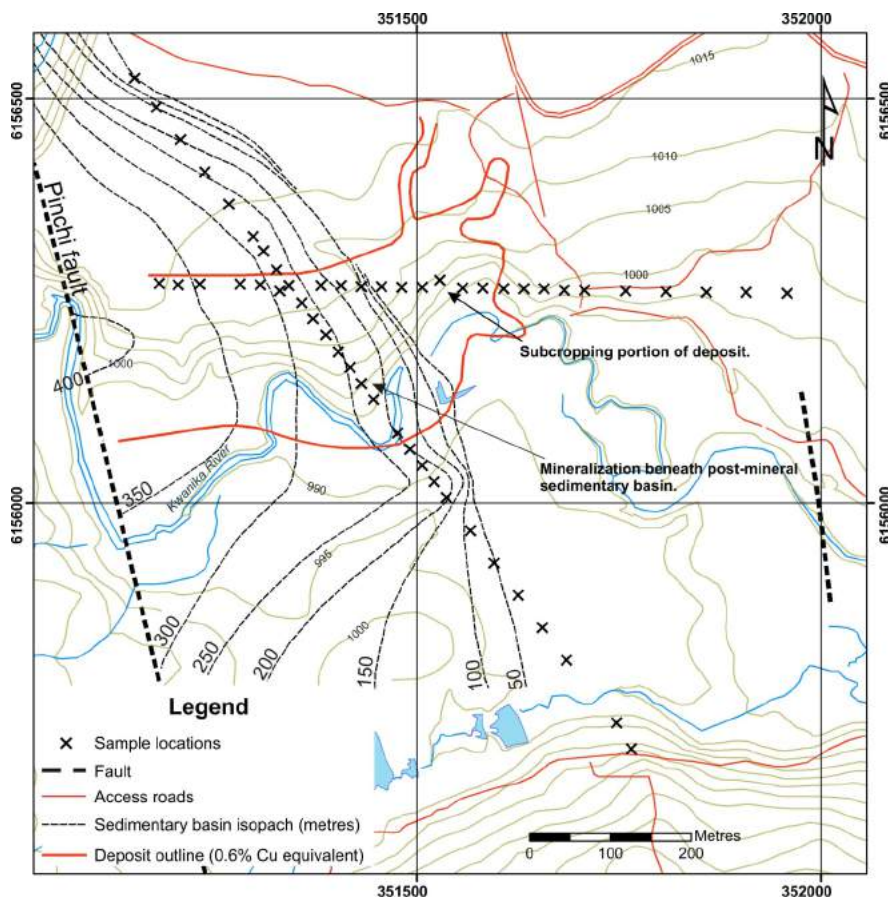


Figure 7. Location map showing the soil profile transects at the Kwanika Central zone, British Columbia.

Kwanika Survey

Two transects of soil profiles (52 samples) were sampled across the Central zone (Figure 7). The east-west transect, which comprises 24 sample sites, passes over the portion of the deposit that subcrops beneath the Quaternary cover. The transect extends from the Pinchi fault in the west to approximately 350 m east of the known mineralization, where drilling indicates that there is no mineralization and background levels exist. A northwest-southeast transect comprising 29 sample sites crosses the portion of the deposit that lies beneath the post-mineral sedimentary basin. In this area, the mineralization is present at a depth of approximately 300 m below surface and is masked by both the post-mineral sedimentary basin and the overlying veneer of Quaternary glacial outwash sediments. The two transects provide different challenges to the DPG methods being tested. Sample sites are spaced at 50 m intervals in inferred background areas and at 25 m intervals over the deposit itself.

Soil pH and conductivity measurements were recorded at the end of each day on material collected from the top centimetre of the mineral soil (usually the top of the Ae or Aej

horizon). This level was chosen based on results presented by Hamilton et. al (2004b) that indicate that the strongest H^+ patterns occur in the uppermost part of the soil profile, or microlayer (Smee, 2009). Conductivity measurements were made on a 1:1 slurry of soil in demineralized water using a VWR International conductivity meter. Measurements of the pH were made on the same slurry using an Oakton® Instruments double junction pHTestr® 30. The instrument was calibrated daily using standard pH buffer solutions at pH 4.00, 7.00 and 10.00. Two pH measurements were taken on each sample: one 20 s after immersion of the electrode into the slurry and a second measurement 20 s after adding one drop of 10% hydrochloric acid and stirring. Measurements of pH were recorded into an Excel spreadsheet and converted to H^+ concentrations. IDH values were also calculated using Smee's (2009) method. Summary statistics for the pH and conductivity measurements are presented in Table 3.

Figure 8 shows profile plots for EC, H^+ , acidified H^+ and IDH along the two transects over the Central zone. Conductivity profiles (Figure 8a) show a relationship to the eastern and southern surface projection of the mineralization as defined by the 0.6% Cu equivalent envelope (Mills, 2008). On the east-west transect, there is an asymmetrical rabbit-ear response slightly offset to the east of the mineralization envelope. The higher contrast peak (11 times the background levels) occurs in the direction of plunge of the mineralization beneath the post-mineral sedimentary basin. An explanation for the apparent offset in the anomaly would be the presence of lower grade subcropping mineralization to the east of the deposit envelope. The strongly anomalous value at the east end of the transect is likely an expression of a prominent north-trending fault zone identified in drillholes to the south of the transect (D. Moore, pers. comm., 2009).

Conductivity values on the northwest-southeast transect show a different pattern. There is a broad but subtle increase in values (over two times the background levels) from north to south over the projection of the mineralization. This culminates in a moderate contrast peak (nine times the background levels) situated directly over the southern edge. There is also an indication of a low-contrast,

Table 3. Summary statistics for soil pH and conductivity measurements, Kwanika and Mount Milligan, British Columbia.

	Kwanika			Mount Milligan		
	Conductivity ($\mu\text{S/cm}$)	pH	Acidified pH	Conductivity ($\mu\text{S/cm}$)	pH	Acidified pH
Number of samples	52	52	52	39	39	39
Minimum	2.7	3.87	2.91	5.2	4.41	2.96
Maximum	36.9	6.07	4.76	30.3	7.66	5.52
Range	34.2	2.2	1.85	25.1	3.25	2.56
Mean	7.72	4.67	3.34	12.58	5.15	3.50
Standard deviation	6.84	0.49	0.46	5.13	0.66	0.60
Variation	46.73	0.24	0.21	26.32	0.43	0.36
Sum	401.50	242.75	173.73	490.60	200.75	136.51
Sum of squares error	5483.05	1145.63	591.24	7171.48	1049.69	491.64
Geometric mean	6.285	4.643	3.314	11.729	5.111	3.458
Median	5.25	4.60	3.18	12.1	5.01	3.27
Mode	3.7	4.00	2.97	12.1	4.46	3.15

rabbit-ear anomaly further to the south. This feature is unexplained.

Hydrogen ion (H^+) profiles are illustrated in Figure 8b. Responses on both transects are relatively noisy but distinct patterns can be seen. On the east-west transect, H^+ values display a general increase over the edges of the mineralization and display a low directly over the centre. While not a classic rabbit-ear response, this pattern is consistent with Hamilton's (1998) model for a reduced overburden column or chimney above sulphide mineralization, which predicts a H^+ low over the mineralized body (Hamilton's [1998] pH measurements were taken at a depth of 25 cm below surface, compared to 7–10 cm in this study). More pronounced lows occur on the northwest-southeast transect. Here, the H^+ response has the form of a double negative or W-shaped profile with the minimum values occurring approximately over the edges of the sulphide body and the central high directly on top of it. The contrasting patterns on the two transects may be an expression of the different depths to the mineralization; i.e., less than 50 m on the east-west transect and approximately 300 m on the northwest-southeast transect.

Negative responses are even more pronounced in the acidified H^+ profiles (Figure 8c). On the east-west transect, a double low or W response is visible slightly to the east of the mineralization envelope. This feature has an antithetic relationship to the conductivity features mentioned above (Figure 8a). Lows are interpreted to be regions where either oxidation of the underlying sulphides is being inhibited by redox conditions in the overburden column, causing a drop in H^+ flux (Hamilton, 1998) or areas of buffering of the acid solution caused by remobilized carbonate (Smee, 1998). A strong negative correlation with conductivity suggests the latter case, where remobilized carbonate is accompanied by other pH sensitive ions in the near surface. A similar W-shaped profile occurs in the acidified H^+ readings on the northwest-southeast transect. The acidified H^+ lows are co-

incident with the edges of the mineralization. Again, there is a strong antithetic relationship with conductivity.

IDH, as mentioned earlier, is a good estimator of the presence of remobilized carbonate. As the inverse of the difference between the acidified and nonacidified H^+ concentrations, high values indicate areas where carbonate has been remobilized and precipitated. Figure 8d shows the IDH profiles for the Kwanika transects. On the east-west transect, there is a very high contrast (66 and 25 times the background levels) asymmetric rabbit-ear response centred slightly east of the projected position of the mineralization. The peaks coincide exactly with the position of the conductivity rabbit-ear response and reinforce the interpretation that they represent redistribution of pH sensitive elements at the surface.

A similar pattern, but with lower contrast, occurs on the northwest-southeast transect. The asymmetrical peaks (13 and 3 times the background levels) fall close to the projected limits of the mineralization. Lower contrast values are likely an expression of the much greater depth to mineralization (>300 m) on this transect.

Mount Milligan Survey

A 3200 m northwest-southeast transect (39 samples) was sampled across the MBX and 66 zone deposits (Figure 5). Samples were spaced at 100 m intervals in background areas at the ends of the transect and at approximately 50 m intervals over the mineralization. Widespread surface disturbance in the deposit area precluded sampling at a regular spacing. Samples were collected from locations that were assessed to have undisturbed profiles. These included roadcuts, exposed roots of first growth trees and isolated enclaves of the original forest preserved between drilling roads. The transect crosses a variety of overburden types, including till and colluvial deposits in the northwest to

glaciofluvial outwash, alluvium and eskers in the centre and southeast (Figure 5).

Soil pH and conductivity measurements were collected using the same procedures employed at Kwanika. Results of the soil EC and pH measurements are shown in Figure 9. EC measurements (Figure 9a) display little contrast between background and mineralized areas. Most of the variation appears to be noise. The only exception being a very subtle peak (2.05 times the background levels) located over

the northwestern boundary of MBX. This feature is barely distinguishable from background values.

Hydrogen ion concentrations (Figure 9b) also display a very low contrast. A subtle, double-peak feature (six and three times the background levels) occurs immediately adjacent to the northwestern boundary of MBX. There is no corresponding peak on the southeastern boundary of the 66 zone, where values are indistinguishable from background levels. A more robust response occurs in the acidified H^+

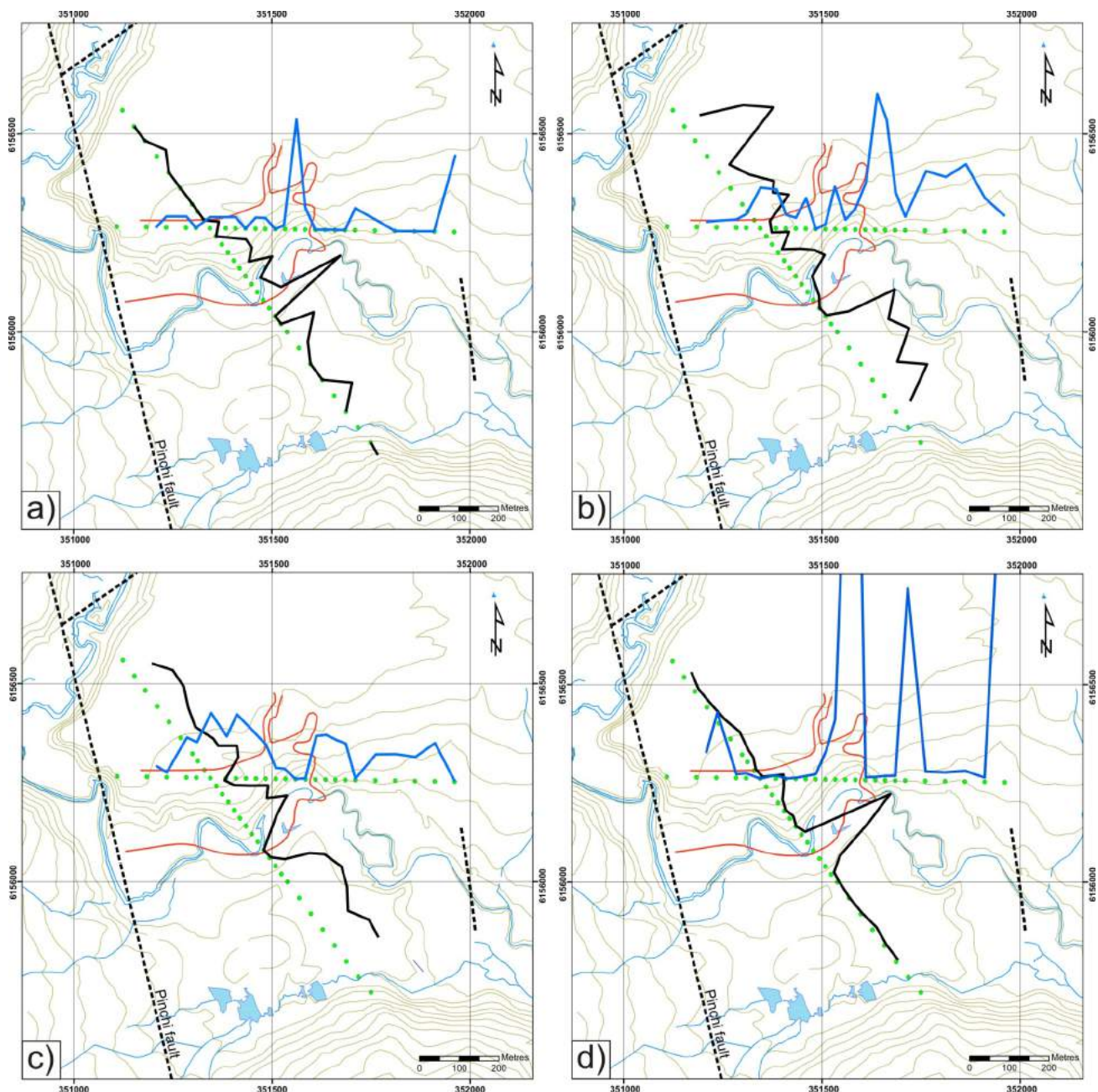


Figure 8. Profiles over the Central zone (red outline), Kwanika, British Columbia: **a)** conductivity; **b)** hydrogen ion concentration; **c)** acidified hydrogen ion concentration; **d)** inverse difference between the acidified and nonacidified hydrogen ion concentrations (IDH).

profile (Figure 9c). Again, the profile is asymmetrical, with the highest values (5.8 times the background levels) occurring adjacent to the northwestern boundary of MBX with no identifiable response on the southeastern boundary of the 66 zone.

The asymmetry of the pH response is highlighted by the IDH profile (Figure 9d). A high-contrast, double-peak feature (39 and 17 times the background levels) can clearly be

seen adjacent to the northwestern boundary of MBX. The peaks show an antithetic relationship with the H^+ profile, strongly suggesting that they are caused by carbonate remobilization in response to changes in the H^+ concentration. Once again there is a lack of a corresponding feature on the southeastern boundary of the 66 zone.

There are two possible explanations for the absence of a rabbit-ear peak on the southeast side of the deposits. As dis-

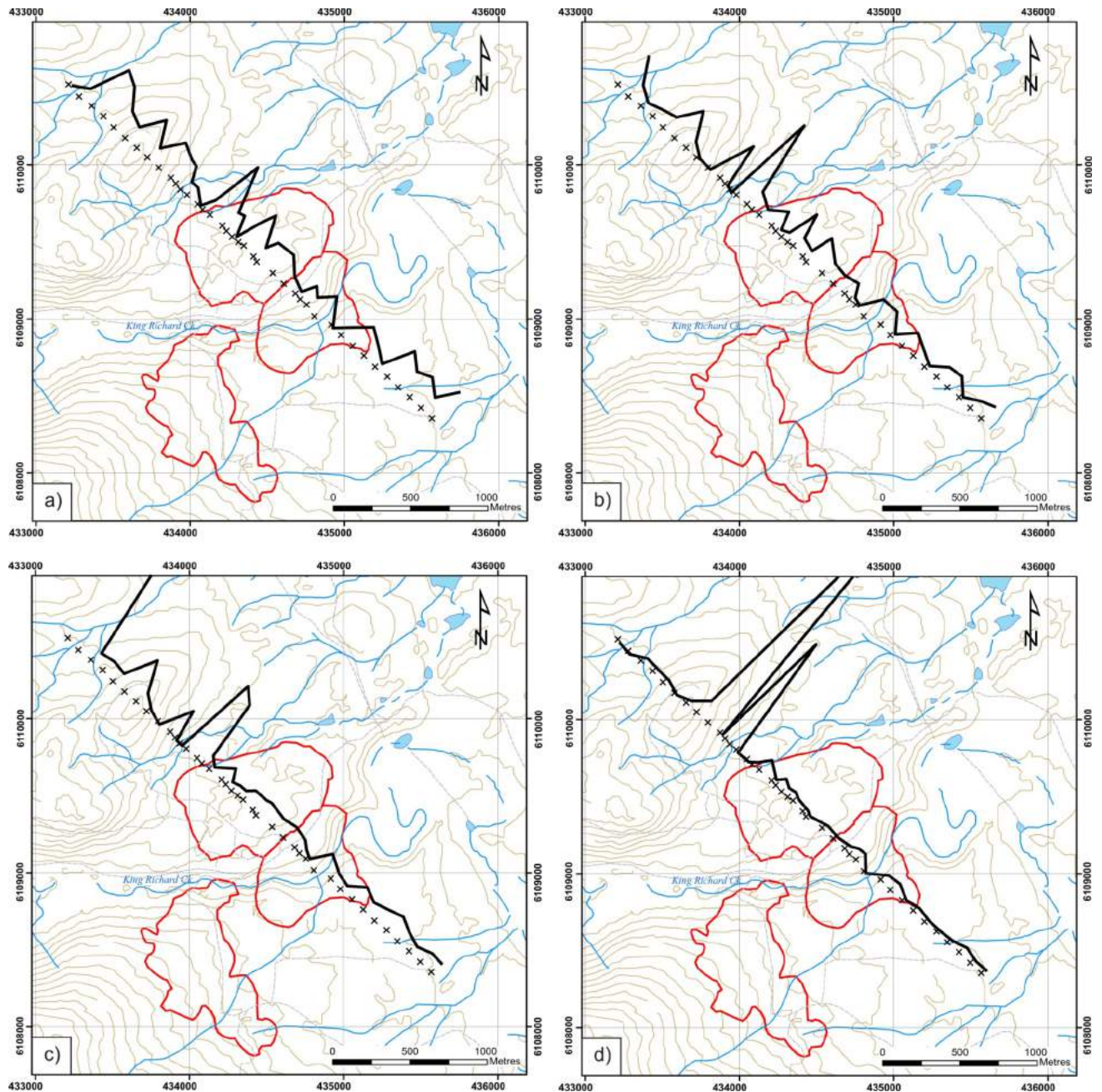


Figure 9. Profiles over the MBX and 66 zone deposits (red outlines) at Mount Milligan, British Columbia: **a)** conductivity; **b)** hydrogen ion concentration; **c)** acidified hydrogen ion concentration; **d)** inverse difference between the acidified and nonacidified hydrogen ion concentration (IDH). Profiles are of response ratios after data levelling to account for overburden type.

cussed earlier, both Smee (1998) and Hamilton's (1998) models predict that there should be an H^+ and IDH peak on both sides of the mineralization. One obvious explanation for the missing peak is surface disturbance. The southeastern boundary of the 66 zone occurs in an area where there has been considerable surface disturbance from road and drill-pad construction. While every effort was made to sample 'pristine' soil profiles, it is possible that the surface is too damaged and the anomaly has been destroyed. The high-contrast, double-peak anomaly on the northwestern boundary of MBX occurs in an area relatively free from disturbance. Another possibility is that the transect does not extend far enough to the southeast to capture the other side of the anomaly. This would be reasonable if there was an extensive zone of low-grade or barren sulphide mineralization extending south of the 66 zone. Drilling southeast of the 66 zone has confirmed the presence of barren pyrite mineralization at depth, however its extent to the south is unknown (D. O'Brien, pers. comm., 2009).

Summary and Conclusions

Part I of this study describes the application and interpretation of soil EC and pH measurements collected over the Kwanika Central zone and the MBX and 66 zone deposits at Mount Milligan. It has been demonstrated that these simple and rapid field measurements appear to detect sulphide mineralization through considerable thicknesses of cover. At Kwanika, the study shows that sulphide mineralization located up to 300 m below the surface has a response consistent with Smee's (1998) model for remobilized and reprecipitated carbonate. IDH patterns define characteristic rabbit-ear anomalies over the edges of the underlying mineralization. At Mount Milligan, a high-contrast IDH anomaly was identified through relatively thin cover immediately adjacent to the northwestern margin of the mineralization. There was no corresponding rabbit-ear response on the southeastern margin of the 66 zone. The lack of a response on the other side might be due to either extensive surface disturbance in that area or the possibility that the sample transect was too short to capture the anomaly. Further work is required to explain this result.

Preliminary conclusions from this study are

Soil pH and EC are low cost, rapid field measurements that appear to effectively detect patterns related to blind sulphide mineralization through considerable thicknesses of transported cover. Blind mineralization can be detected in the field using nothing more sophisticated than a Teflon beaker, demineralized water, an acid drop-per bottle and conductivity and pH meters.

Responses to mineralization in undisturbed areas show classic rabbit-ear patterns with peaks located over or immediately adjacent to the edges of the underlying sulphide mineralization. In temperate boreal forest environments of north-central BC, the signal is strongest in

the IDH, suggesting that carbonate remobilization is occurring in response to subtle changes in pH at the surface.

Both soil EC and pH appear to show a response to mineralization through tens of metres of Quaternary cover at Kwanika, and are able to indicate mineralization through hundreds of metres of post-mineral sediments.

Amplitude of the signal appears to be related to the thickness of the cover. At Kwanika, maximum contrast occurs where the mineralization is subcropping beneath tens of metres of overburden. Where sulphides occur at considerable depth, beneath 300 m of post-mineral sediments and Quaternary cover, contrast is lower but the patterns remain the same.

At Mount Milligan, additional work is required to determine why the southeastern rabbit-ear response is missing. This would involve resampling the southeastern margin of the 66 zone using alternate sample sites and extending the sample transect further to the southeast.

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