Drift Prospecting within the QUEST Project Area, Central British Columbia (NTS 093J): Potential for Porphyry Copper-Gold, Volcanogenic Massive Sulphide Mineralization and Gold-Copper Veins

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Ward, B.C., Leybourne, M.I. and Sacco, D.N. (2011): Drift prospecting within the QUEST Project area, central British Columbia (NTS 093J): potential for porphyry copper-gold, volcanogenic massive sulphide mineralization and gold-copper veins; *in* Geoscience BC Summary of Activities 2010, Geoscience BC, Report 2011-1, p. 73–96.

Introduction

The Interior Plateau region of central British Columbia has experienced a major outbreak of mountain pine beetle, which has decimated pine forests in the region causing a significant economic downturn in forestry-dependent communities (e.g., Abbott et al., 2009; Coops and Wulder, 2010; Woods et al., 2010; Wulder et al., 2010). Geoscience BC's Quesnellia Exploration Strategy (QUEST) Project is designed to stimulate mining exploration and provide employment opportunities to those adversely affected by this decline in forestry jobs (e.g., Nelsen et al., 2010). The QUEST Project area has good potential for Cu-Au porphyry and volcanogenic massive sulphide (VMS) mineralization, but mineral exploration activity has been hindered in some areas due to the thick cover of surficial deposits. Regional-scale till sampling can be carried out to assess the mineral potential of areas covered with thick glacial deposits (Levson, 2001; McClenaghan et al., 2002; McClenaghan, 2005). Detailed investigations of till samples with elevated or anomalous values, at a regional scale, can help identify potentially mineralized zones within covered bedrock units. The preferred sampling medium for till geochemical surveys is basal till, as it is commonly considered a first derivative of bedrock (Dreimanis, 1989; Levson, 2001). Knowledge of the glacial history, specifically the ice-flow history and dominant transport direction, is vital to the interpretation of geochemical survey data from the area.

The objective of this study is to use regional-scale major-, minor- and trace-element till geochemical data (by inductively coupled plasma–mass spectrometry [ICP-MS] following aqua-regia digestion, instrumental neutron activation analysis [INAA], gold grain counts and heavy mineral separations) to identify mineralized bedrock and predict bedrock lithologies. These data will provide new exploration targets and also provide geological context for companies to interpret their own geochemical and geological datasets. This paper is a summary of a future Geoscience BC publication that will include all data tables, statistical analysis and proportional dot maps of elements analyzed. In the interests of brevity, data for some of the elements mentioned here are not shown.

Keywords: *geochemistry, regional till geochemical survey, Cu-Au porphyry, VMS*

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Bedrock and Quaternary Geology Background

The study area occurs in the heart of the QUEST Project area, northwest of the city of Prince George (Figure 1). The majority of this area lies in the relatively low relief area of the Interior Plateau (Mathews, 1986), including its subdivisions, the Fraser Basin and Nechako Plateau. It is characterized by glacial lake deposits, drumlinized drift, and glaciofluvial outwash and esker deposits (Holland, 1976).

Regional Quaternary Framework

The study area was repeatedly affected by the Cordilleran Ice Sheet over approximately the last two million years (Armstrong et al., 1965; Clague, 1989), the most recent being during the Fraser glaciation. The major sources of regional ice that covered the study area advanced from accumulation centres in the Coast, Skeena and Cariboo mountains (Tipper, 1971a, b; Levson and Giles, 1997; Plouffe, 1997, 2000; Figure 1). The ice-flow history of the study area was determined by compiling and combining ice-flow information from existing maps (Tipper, 1971a; Clague, 1998a, b; Blais-Stevens and Clague, 2007), together with observations made in the field (Sacco et al., 2010). Ice-flow indicators measured in the field by Ward et al. (2009) and Sacco et al. (2010) were mainly microflow indicators such as grooves, striations and rat tails. The dominant ice flow (Sacco et al., 2010; Figure 2) was determined by combining data from macroforms (drumlins, flutings, streamlined bedrock) and microforms (striations, grooves, rat tails). These

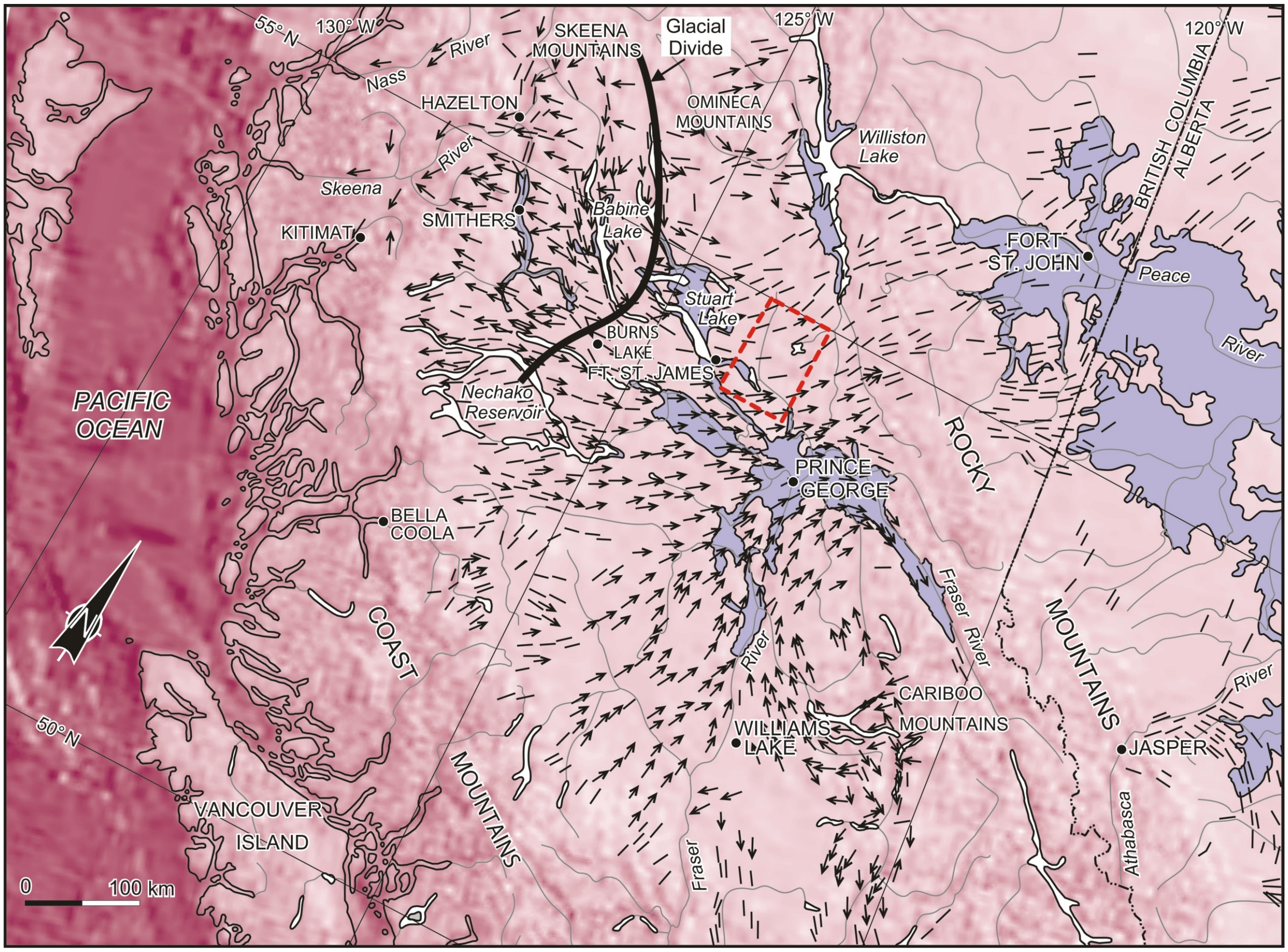

Figure 1. Northern British Columbia with dominant ice-flow directions (shown by the black arrows and short black lines) for the Late Wisconsinan Fraser glaciation (modified from Stumpf et al., 2000). Light blue areas indicate the approximate distribution of deglacial lake sediments, which can be a hindrance to drift prospecting. Red dashed line delineates the study area, which is shown in detail in Figure 2.

data suggest that it was mainly ice from the Coast Mountains to the west and south, and to a lesser extent ice from the Cariboo Mountains, that covered the area. Little information exists on ice flow during the glacier's advance into the area, but it is likely that ice flowed eastward from the Coast Mountains and was subsequently deflected to the northeast by interaction with ice flowing north from sources in the Coast and Caribou mountains to the south. The dominant ice flow, and thus main sediment transport, was northeasterly with minor deviations to a more northerly direction in the north and a more easterly direction in the southern portions of the study area. Evaluation of till geochemical anomalies should concentrate on these dominant flow directions. Striation and till fabric data indicate ice flow was more westerly during deglaciation, which would also influence interpretation of anomalies. More information on the glacial history is given in Sacco et al. (2010).

Regional Bedrock Framework

The study area straddles four of the terranes that make up the Canadian Cordillera (Cache Creek, Slide Mountain, Quesnel, Kootenay) while the most northeastern corner of it extends into the Rocky Mountain assemblage (Figure 2). A complex assemblage of intrusive and extrusive rocks of the Slide Mountain terrane occurs in the east. The Cache Creek terrane is composed of Pennsylvanian and Permian limestone in the southwestern portion of the study area, with basalts occurring just to the south. The Rocky Mountain assemblage in the northeastern corner of the study area comprises Silurian to Devonian sandstone and quartzite. The Quesnel terrane dominates the study area and is composed primarily of Late Triassic to Early Jurassic arc volcanic rocks of the Witch Lake succession and volcaniclastic rocks of the Cottonwood River succession, both part of the Nicola Group (Logan et al., 2010). The Nicola Group was

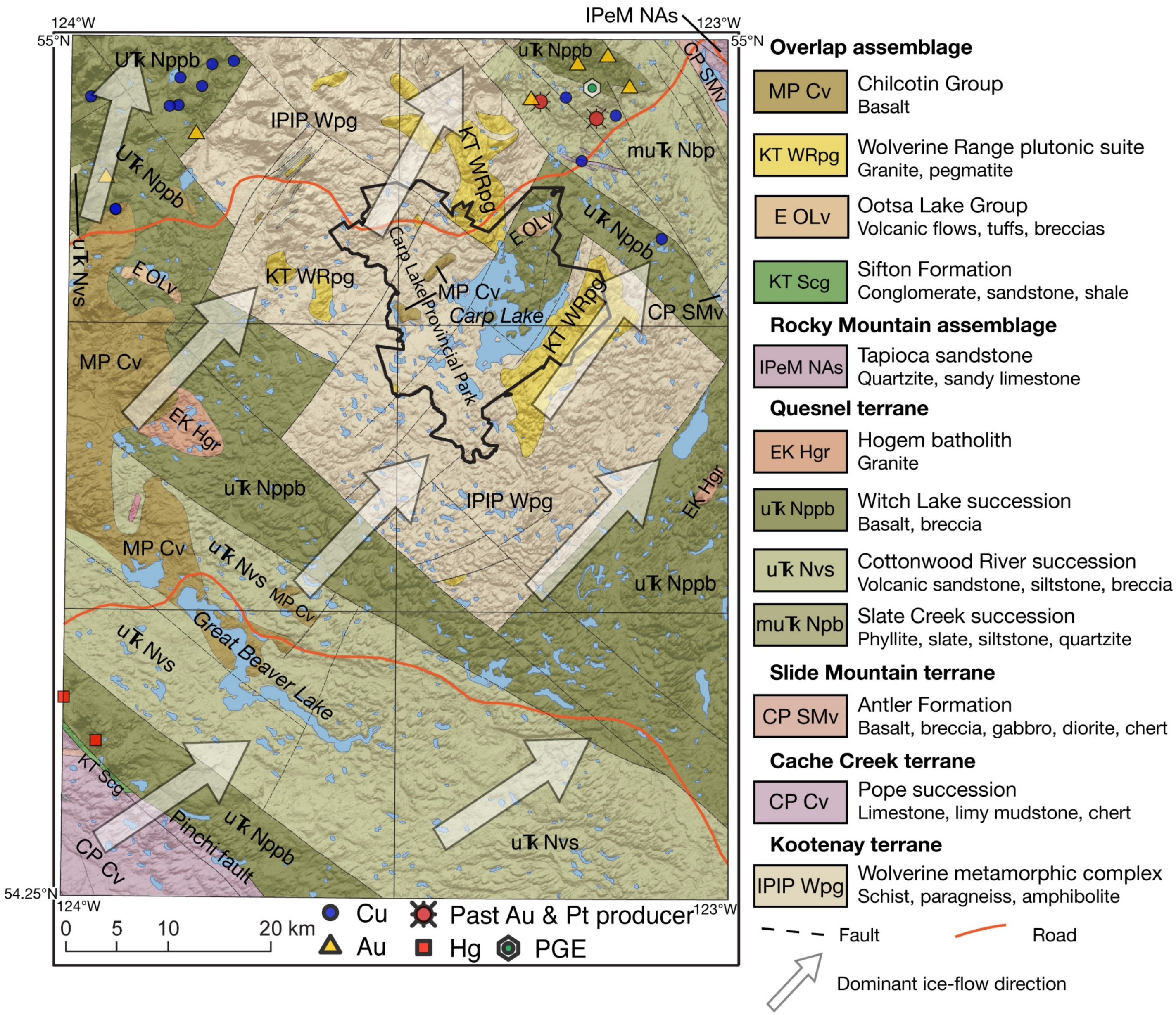

Figure 2. Major bedrock geological units of the study area, central British Columbia (modified from Struik, 1994 and Logan et al., 2010). Also shown are mineral occurrences for different commodity types (after BC Geological Survey, 2010) and the dominant ice-flow direction (light-coloured arrows; after Sacco et al., 2010).

previously referred to as the Takla Group (Struik, 1994), following first usage. It was correlated with Takla Group rocks to the west within the Stikine terrane. The Nicola Group comprises: a) mainly basaltic to dacitic volcaniclastic rocks and subordinate coherent volcanic rocks, each with augite-porphyry textures (particularly characteristic of the Quesnel terrane), which form an eastern facies of alkaline to subalkaline augite-phyric basaltic andesite; b) coeval and partly comagmatic plutons ranging from calcalkaline (in the west) to alkaline (in the east); and c) sedimentary rocks, including shale, limestone and epiclastic deposits.

Stratigraphically overlying these terranes are a series of overlap assemblages ranging from Upper Cretaceous to Miocene sedimentary rocks and Cretaceous to Pliocene volcanic rocks. The latter includes the dominantly Miocene Chilcotin basalts and Eocene felsic volcanic rocks. Intrusive rocks, paragneiss and metasedimentary rocks of the Wolverine metamorphic complex were exposed during Eocene extension. The metamorphism and plutonism occurred in the late Cretaceous and Paleogene, and the protolith for the paragneiss and metasedimentary rocks are likely Precambrian and Early Paleozoic (Struik, 1994). Recent compilation has assigned these rocks to the Kootenay terrane (Logan et al., 2010).

Within the study area, the BC Ministry of Forests, Mines and Lands mineral inventory database (MINFILE; BC Geological Survey, 2010) lists twelve Cu showings, six Au showings, one platinum group elements (PGE) showing, two Hg showings and two past-producing Au and Pt deposits (Figure 2).

The two past producers are the McDougall River and McLeod River placer deposits (MINFILE 093J 007, 093J 012; BC Geological Survey, 2010). Both deposits occur in the northeastern part of the study area, underlain primarily by Mississippian Slide Mountain Group. Cariboo Northern Development Co. Ltd. and Northern Reef Gold Mines Ltd. worked the McDougall River placer mineralization from around 1931 to 1935, with total production of approximately 1750 g (62 oz.). From 1981 to present, the area has received renewed interest, including heavy mineral, soil, silt and rock sampling; geological mapping; airborne very low frequency (VLF) and magnetometer surveys; and ground VLF and magnetometer surveys by a variety of companies. At McDougall River, Au and Pt were extracted from shallow gravel deposits on both banks of the river, with additional clasts retrieved from cracks and crevices in the bedrock. Local sheared rocks and quartz veins may be the source of the placer Au and PGE. Heavy mineral samples have yielded high Au and Ag contents, and many of the placer Au grains recovered are angular to wiry, consistent with minimal transport from a local bedrock source. The coincident electromagnetic (EM) and magnetic anomalies could represent the local source for Au.

The two Hg showings (Mount Prince Southeast and Northwest, MINFILE 093J 010, 093J 011) in the southwestern part of the study area are associated with the Pinchi fault. Both showings are characterized by small volumes of cinnabar hosted by carbonate-altered and sheared Takla Group mafic volcanic rocks, commonly associated with quartz stringers. Most of the other mineral showings in the study area are small with minimal associated exploration activity.

Mount Milligan is a Cu-Au porphyry developed prospect (MINFILE 093N 194) to the northwest of the study area in the Quesnel terrane. In this area, Triassic to Lower Jurassic volcanic and subordinate sedimentary rocks of Nicola Group are interpreted to be the extrusive phase of the Hogem intrusive suite. Many Cu-Au mineral showings are associated with the Hogem batholith and smaller coeval intrusions. The Nicola Group in the Mount Milligan area is informally subdivided into a lower, predominantly sedimentary Inzana Lake succession, and an upper, predominantly volcaniclastic Witch Lake succession. The Witch Lake succession hosts the Mount Milligan deposit, and is characterized by augite-phyric volcaniclastic and coherent basaltic andesite, with subordinate epiclastic beds. Regional mapping and petrographic studies in the Mount Milligan area indicate that the Witch Lake basaltic andesite and associated sedimentary rocks have been subjected to strong potassic alteration up to 4 km from the deposit. Witch Lake succession volcanic rocks were intruded by syn- and post-depositional gabbro, diorite, granodiorite, monzonite and syenite (Logan et al., 2010).

Field and Analytical Methods

Field Sampling

Basal till samples were collected at a total of 712 sites. Basal till in this area is a dense, dark grey, matrix-supported diamicton and is composed of 25–40% gravel-sized material (clasts) with a typically sandy silt matrix. Overall sample density is about 1 sample/7.5 km^2 but there are some zones with no samples and some zones with higher density. In some areas, sampling was not possible because of road deactivation or lack of roads, and/or a lack of suitable sample media, such as in areas of eolian, glaciofluvial and glaciolacustrine deposits. In addition, no sampling occurred within Carp Lake Provincial Park (Figure 2).

The sampling regime included collecting three separate samples, approximately 800–900 g each, at each sample site for: a) analysis of the clay-sized (hereafter referred to as clay) fraction by aqua-regia digestion followed by inductively coupled plasma–mass spectrometry (ICP-MS) at Acme Analytical Laboratories Ltd. (Vancouver, BC); b) analysis of the clay plus silt–sized (hereafter referred to as clay+silt) fraction by instrumental neutron activation analysis (INAA) at Activation Laboratories Inc. (Ancaster, Ontario); and c) archiving at the Geological Survey of Canada (GSC). In addition, at every 4–5 sites, a >10–15 kg sample was collected for heavy mineral separation and gold grain counts. The heavy mineral separations and counts were conducted at Overburden Drilling Management Limited (Nepean, Ontario). The <0.25 mm fraction of the heavy mineral concentrates were then analyzed by INAA at Becquerel Laboratories Inc. (Mississauga, Ontario).

Analytical Methods

The clay+silt fraction of till samples (on average, 24 g of material was used) were analyzed for 35 elements by INAA (1D Enhanced) at Activation Laboratories Ltd. The INAA method has been described previously by Hoffman (1992) and details of the procedure can be found in Activation Laboratories Ltd. (2010). The following description summarizes the procedure. An aliquot and an internal standard (one for every eleven samples) are irradiated with flux wires at a thermal neutron flux of 7×10^{12} $n \cdot cm^{-2} \cdot s^{-1}$. After a seven-day decay, the samples are counted on a high purity Ge detector. Using the flux wires, the decay-corrected activities are compared to a calibration. The standard included is only a check on accuracy and is not used for calibration purposes. From 10 to 30% of the samples are rechecked by remeasurement. For all analytes, except Au, a 1 g aliquot is used. For Au a 30 g size, if available, is used.

Samples were processed to extract the clay at Acme Analytical Laboratories Ltd. (Vancouver, BC). Typically, between 0.5 and 0.8 kg of till were processed, which yielded approximately 5 g of clay, on average. The clay splits were analyzed by ICP-MS for 36 elements (1DX) following leaching in a hot (95°C) aqua-regia digestion. Up to 5 g of clay is processed to overcome nugget effects for Au.

Heavy mineral concentrates (HMC) were separated on large till samples at Overburden Drilling Management Limited. A total of 122 samples of 10–15 kg were panned for gold grains, platinum group metals (PGM) and uraninite. Bulk samples were disaggregated, followed by separation of the >2 and <2 mm fractions. The <2 mm fraction is then pre-concentrated on a shaking table, with the <0.25 mm fraction subsequently separated using heavy liquid (specific gravity of 3.2 g/cm^3). Panned Au, uraninite and PGM are then examined under optical microscope to provide grain counts as well as grain morphology. More detailed descriptions of the methods are provided in Averill (2001) and McClenaghan et al. (2002). Sulphide and cinnabar grains were also counted, although where the number of grains was >20, these counts are estimates.

The selected results of the analyses are discussed below; those elements with the most significance to potential mineralization in this project area are discussed. A future Geoscience BC publication will include all of the data for all of the elements analyzed.

To quantify the accuracy and precision of these analytical data, a combination of field duplicates, analytical duplicates and reference standards are used. For every 20 samples collected in the field, one field duplicate is collected, one analytical duplicate is split and inserted into the sample sequence at the lab, and one reference standard (either an in-house BCGS standard or a certified Canada Centre for Mineral and Energy Technology [CANMET] standard) is inserted. For the aqua-regia digestion followed by ICP-MS method, precision for most analytes is <5% relative standard deviation (RSD) at 10 times the detection limit. Closer to the detection limit, most analytes still have RSD values of <10%. Similarly, for analytes above the detection limit, the INAA data are generally very good with precision generally <5% RSD, and accuracy generally <3%, except W at 5%.

Results

Au, As, Ag and Hg Contents

Gold contents in the clay fraction show clearly anomalous values around the 98th percentile (10 ppb), although there is also a subtle change in slope around the 90th percentile, or 8 ppb (Figure 3a). Gold contents in the clay fraction range from less than detection (0.5 ppb) to 294 ppb (average = 5.1 ±11 ppb, n = 704). For the clay+silt fraction, anomalous Au contents occur above the 80th percentile (~8 ppb; Figure 3a); most samples below this threshold were below the detection limit by this method (2 ppb). In the clay+silt fraction, Au contents range up to 635 ppb. Anomalous Au contents occur in the northeastern and northwestern parts of the map area for both size fractions, largely coincident with known Au showings (Figures 4a, b). There are also anomalous Au contents, in particular in the clay+silt fraction, to the south, and to a lesser extent, to the east of Carp Lake. There are no known Au showings here. Gold shows the best correlation with Cu (r = 0.410).

Arsenic is typically considered a pathfinder element for Au. In this study, threshold As contents in till are ~32 and 26 ppm, at the 95th and 98th percentiles for the clay and clay+silt fractions, respectively (Figure 3a). Arsenic contents are anomalous in both the northeastern and northwestern sections of the study area (Figures 4c, d), largely coincident with Au anomalies. However, As contents do not appear to be anomalous south of Carp Lake; in contrast, there are moderately anomalous As contents in the west-central part of the study area, primarily in the clay+silt fraction. Au and As show a moderately positive correlation (r = 0.372) for the clay fraction based on the R-mode factor analysis, statistically significant at the 99.9% confidence interval. By contrast, the correlation between As and Au for

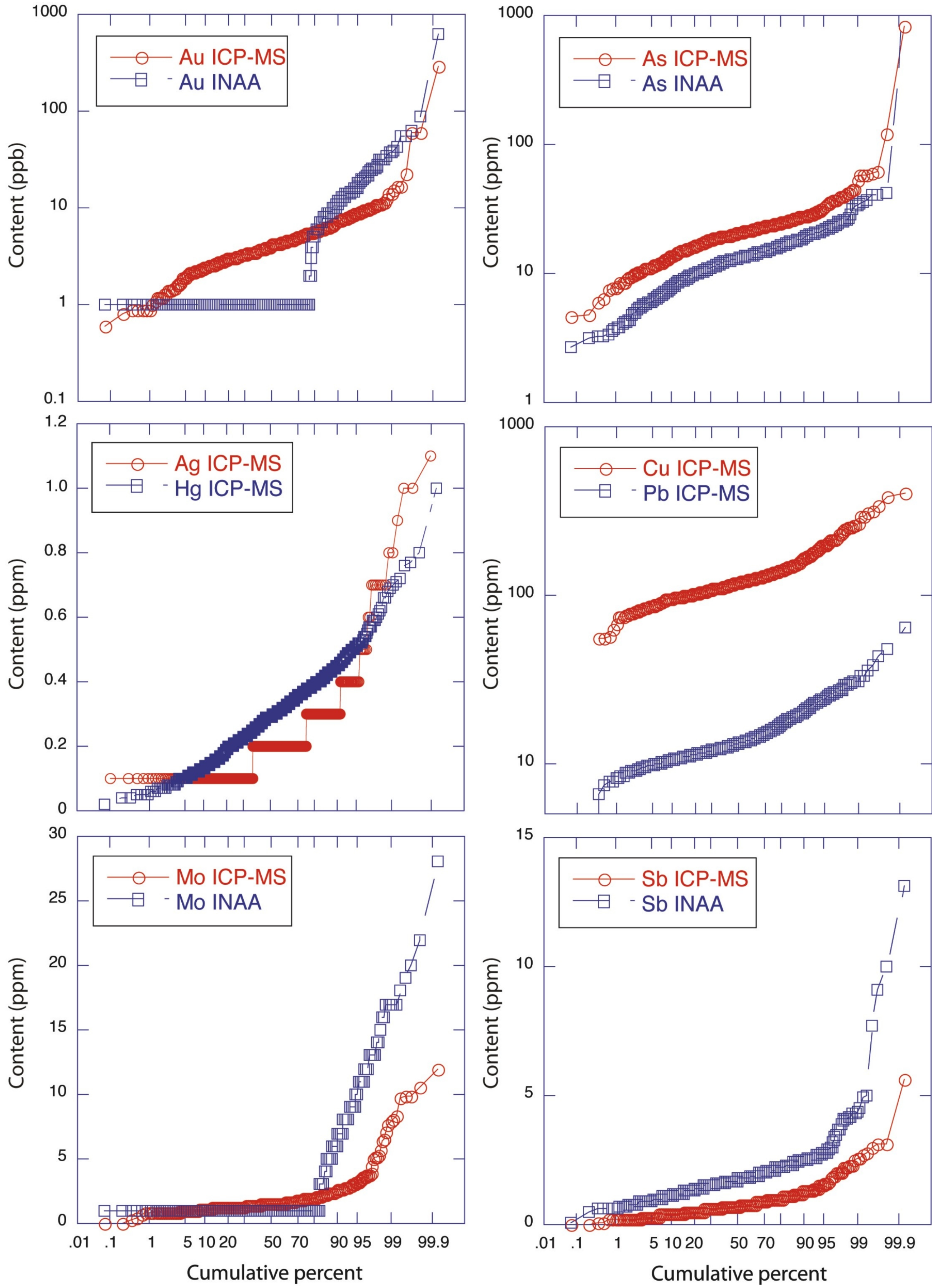

Figure 3a. Cumulative probability plots for Au, As, Ag, Hg, Cu, Pb, Mo and Sb, analyzed by aqua-regia digestion followed by inductively coupled plasma–mass spectrometry (ICP-MS) on the clay-sized fraction and/or instrumental neutron activation analysis (INAA) on the clay plus silt–sized fraction. Anomalous metal concentrations typically occur around the 90 to 95th percentiles, where there is a change in slope on the probability plot.

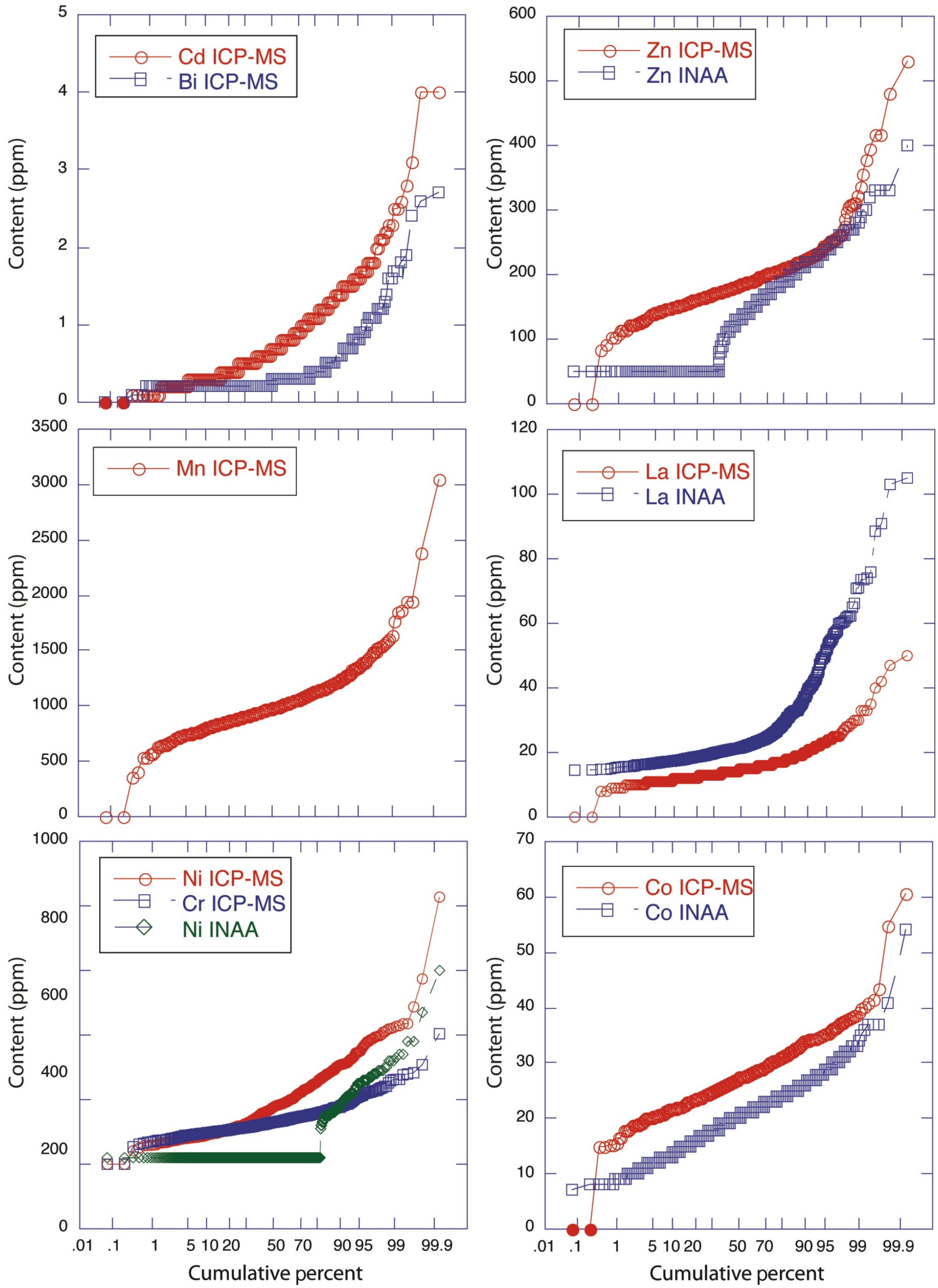

Figure 3b. Cumulative probability plots for Cd, Bi, Zn, Mn, La, Ni, Cr and Co, analyzed by aqua-regia digestion followed by inductively coupled plasma–mass spectrometry (ICP-MS) on the clay-sized fraction and/or instrumental neutron activation analysis (INAA) on the clay plus silt–sized fraction. Anomalous metal concentrations typically occur around the 90 to 95th percentiles, where there is a change in slope on the probability plot.

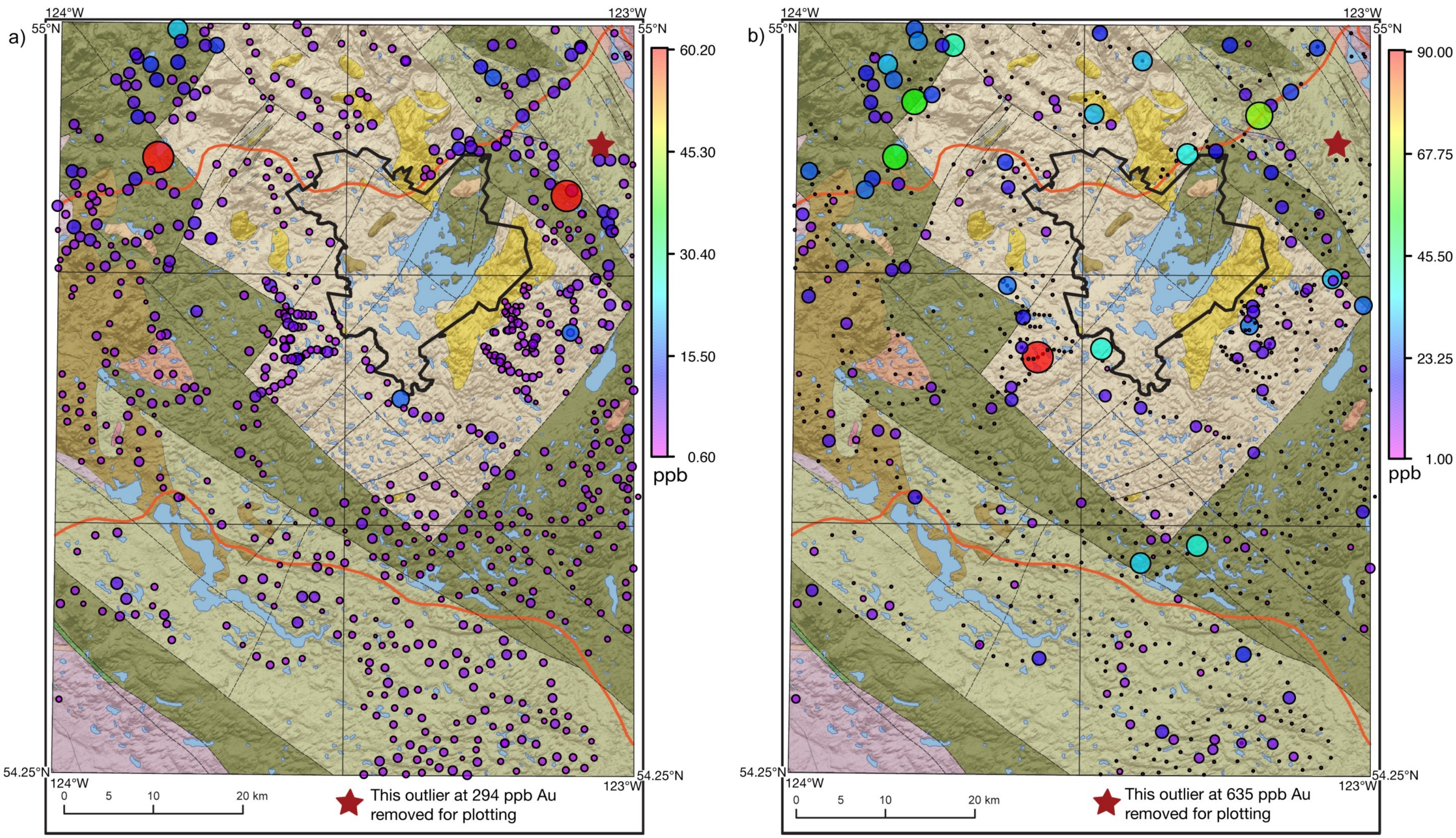

Figure 4. Proportional dot maps of selected elements from till geochemical analyses, central British Columbia: **a)** Au contents (clay-sized fraction) by inductively coupled plasma–mass spectrometry (ICP-MS) and **b)** Au contents (clay plus silt–sized fraction) by instrumental neutron activation analysis (INAA). Size of dots are proportional to the content. Data are overlaid on the bedrock geology map presented in Figure 2.

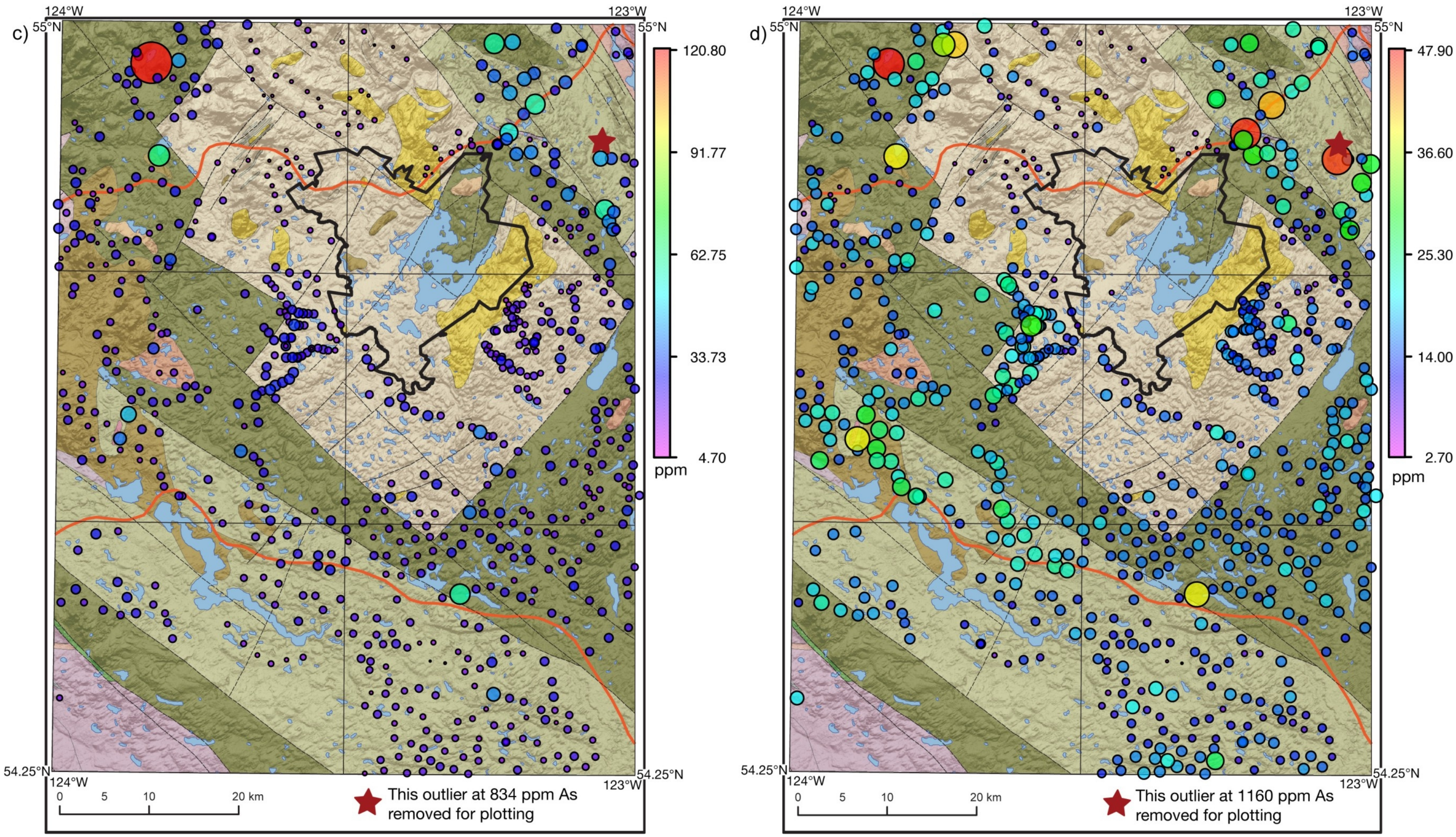

Figure 4 (continued). Proportional dot maps of selected elements from till geochemical analyses, central British Columbia: **c)** As contents (clay-sized fraction) by ICP-MS and **d)** As contents (clay plus silt–sized fraction) by INAA. Size of dots are proportional to the content. Data are overlaid on the bedrock geology map presented in Figure 2.

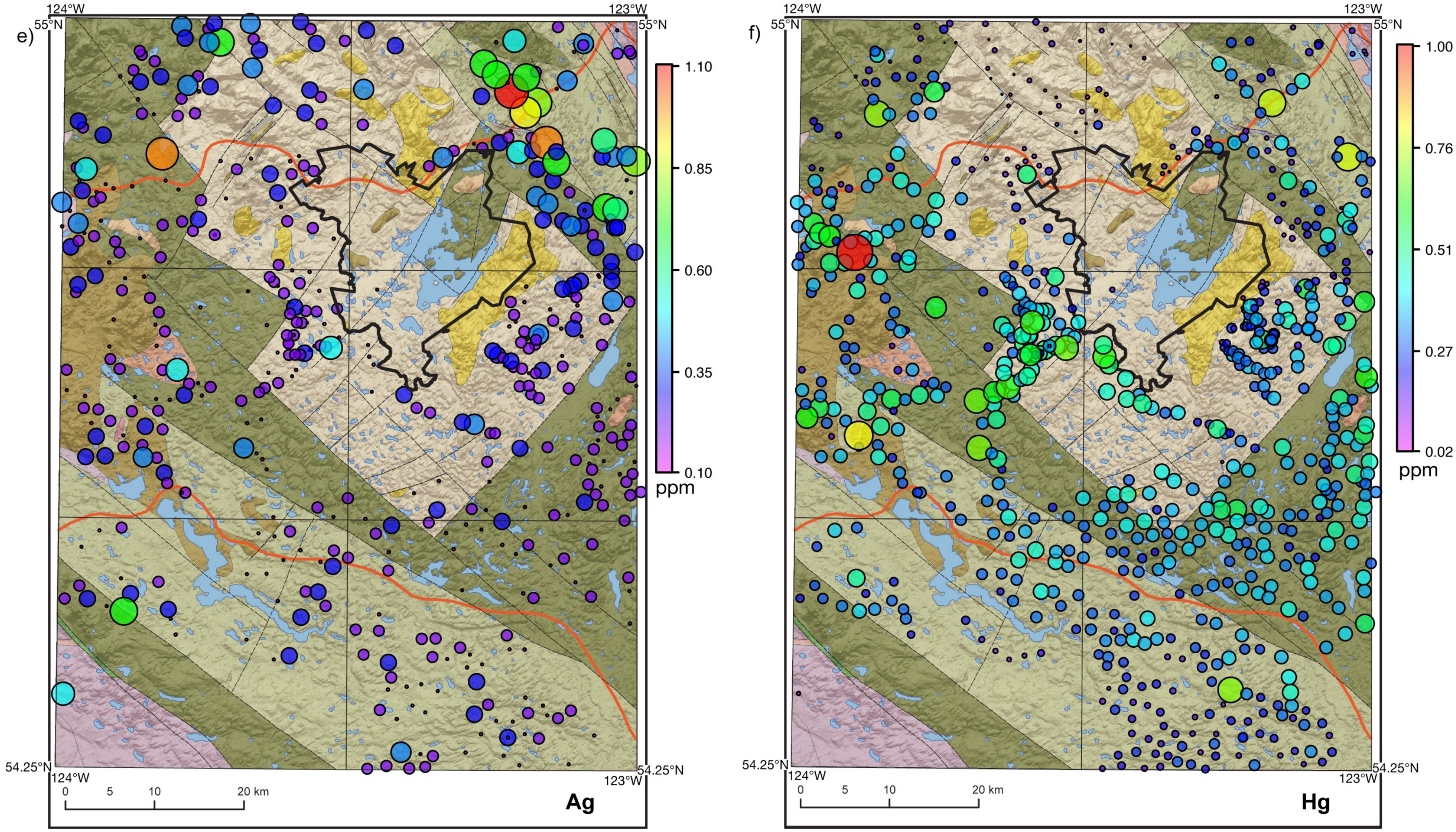

Figure 4 (continued). Proportional dot maps of selected elements from till geochemical analyses, central British Columbia: **e)** Ag contents (clay-sized fraction) by ICP-MS and **f)** Hg contents (clay-sized fraction) by ICP-MS. Size of dots are proportional to the content. Data are overlaid on the bedrock geology map presented in Figure 2.

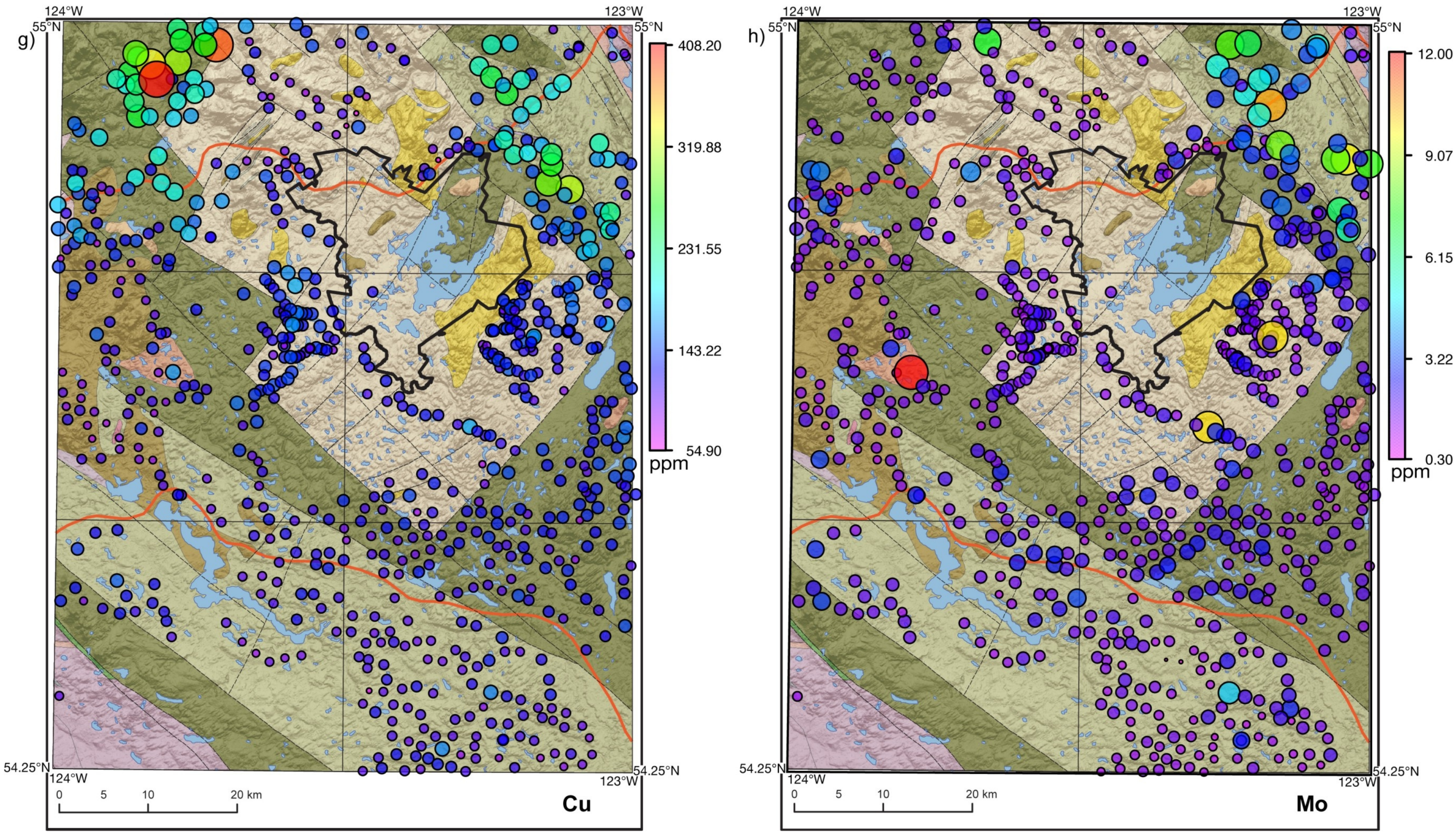

Figure 4 (continued). Proportional dot maps of selected elements from till geochemical analyses, central British Columbia: **g)** Cu contents (clay-sized fraction) by ICP-MS and **h)** Mo contents (clay-sized fraction) by ICP-MS. Size of dots are proportional to the content. Data are overlaid on the bedrock geology map presented in Figure 2.

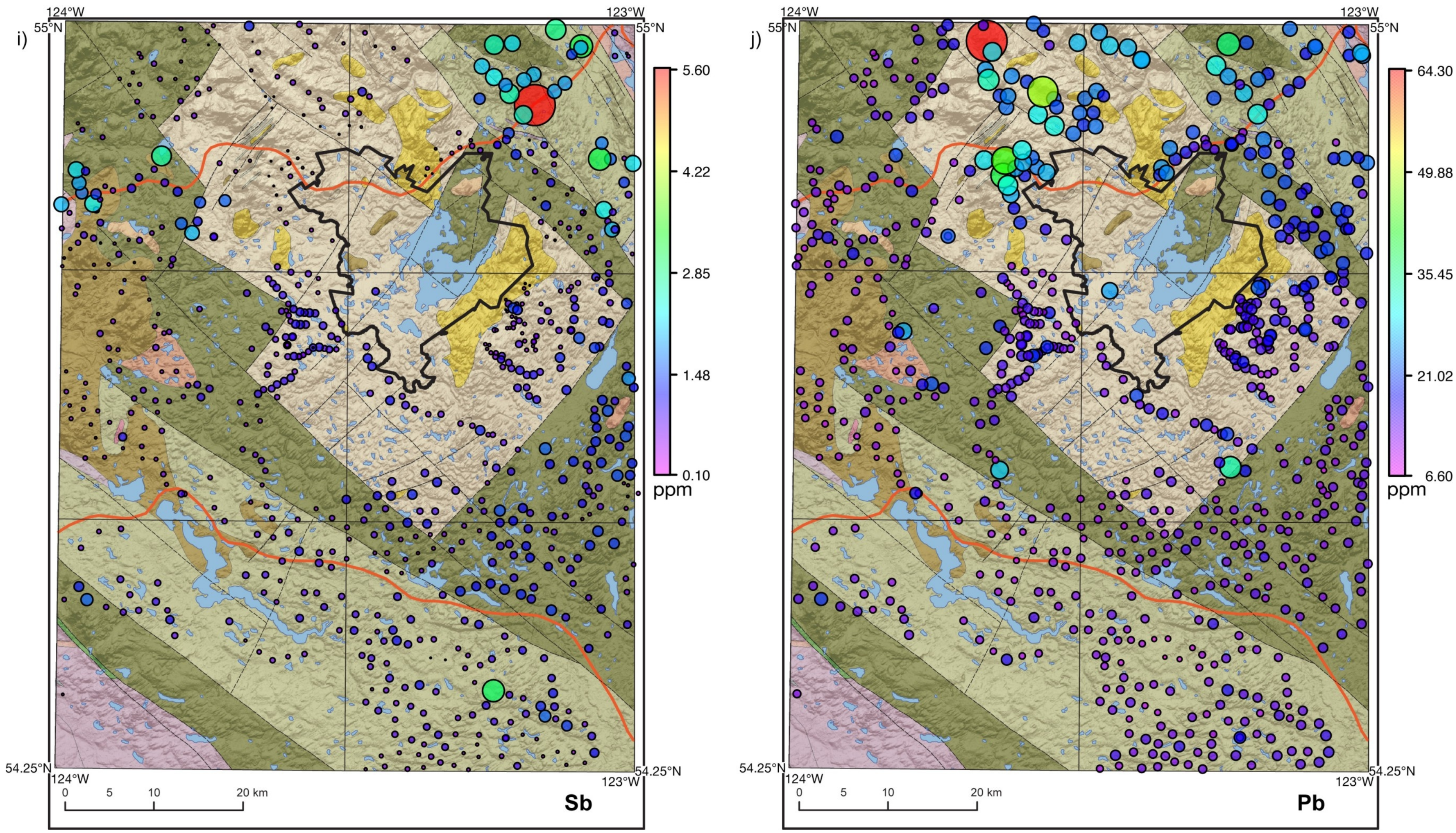

Figure 4 (continued). Proportional dot maps of selected elements from till geochemical analyses, central British Columbia: **i)** Sb contents (clay-sized fraction) by ICP-MS and **j)** Pb contents (clay-sized fraction) by ICP-MS. Size of dots are proportional to the content. Data are overlaid on the bedrock geology map presented in Figure 2.

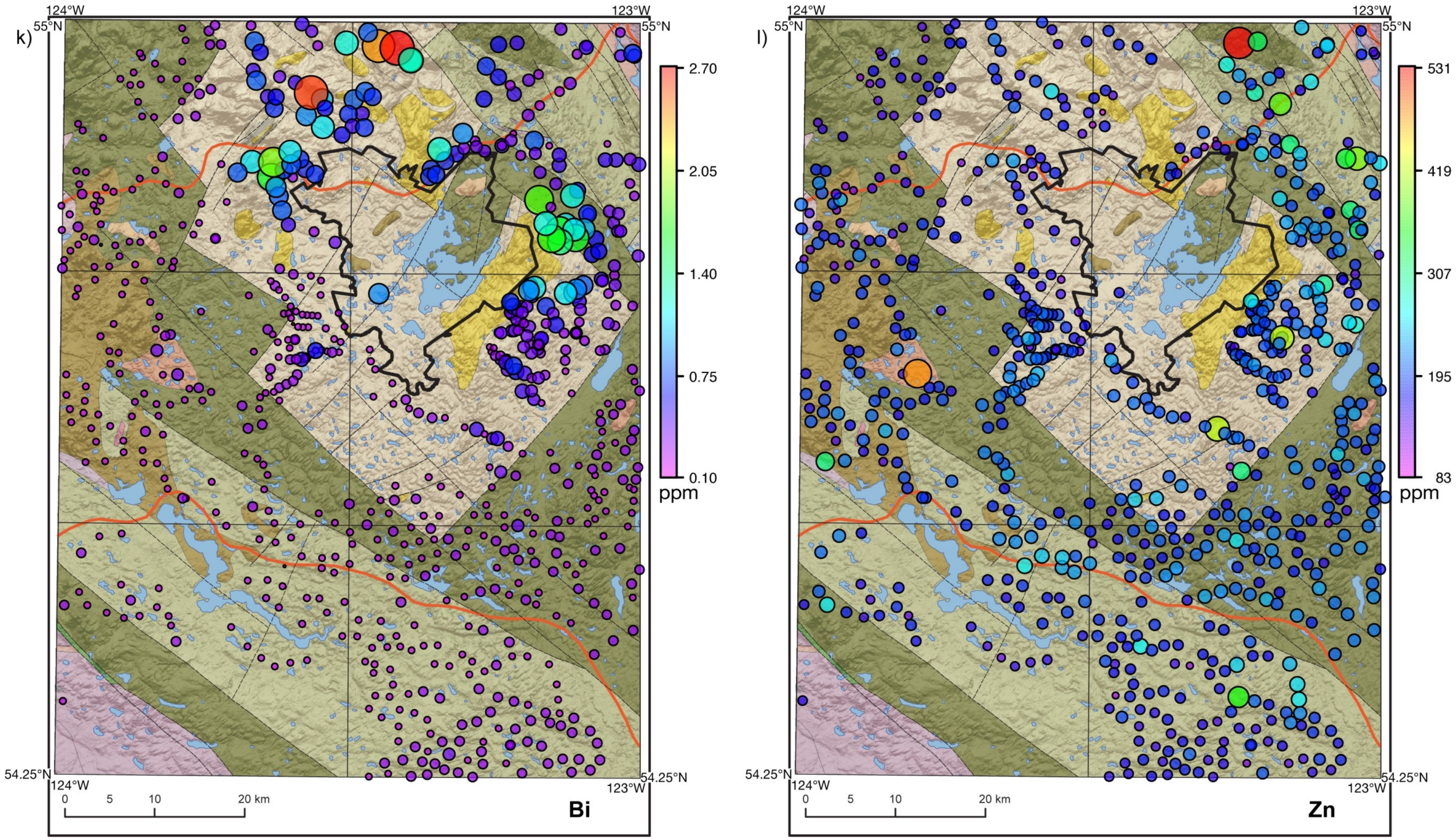

Figure 4 (continued). Proportional dot maps of selected elements from till geochemical analyses, central British Columbia: **k)** Bi contents (clay-sized fraction) by ICP-MS and **l)** Zn contents (clay-sized fraction) by ICP-MS. Size of dots are proportional to the content. Data are overlaid on the bedrock geology map presented in Figure 2.

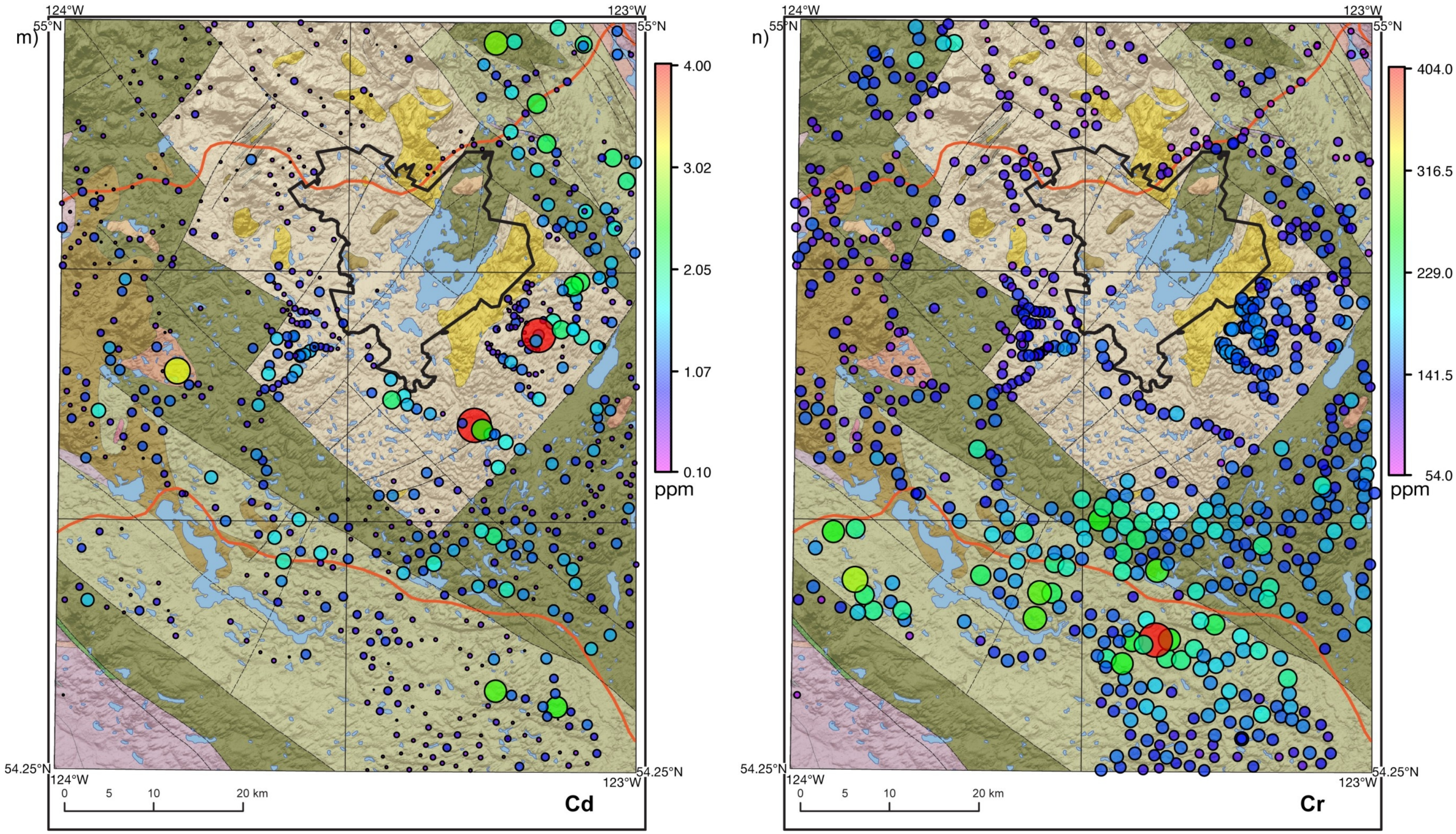

Figure 4 (continued). Proportional dot maps of selected elements from till geochemical analyses, central British Columbia: **m)** Cd contents (clay-sized fraction) by ICP-MS and **n)** Cr contents (clay-sized fraction) by ICP-MS. Size of dots are proportional to the content. Data are overlaid on the bedrock geology map presented in Figure 2.

the clay+silt fraction is poor (r = 0.112), despite the evident spatial association (Figures 4b, d).

Silver contents for the clay fraction range from less than detection (0.1 ppm) to 1.1 ppm (average = 0.21 ±0.14 ppm, n = 520), with anomalous values >0.5 ppm (~95th percentile; Figure 3a). Silver shows a moderately positive, statistically significant correlation (r = 0.313) with Au, with anomalous values in the northeastern and northwestern parts of the study area (Figure 4e), being coincident with the Au anomalies. Silver for the clay+silt fraction was below the 5 ppm detection limit for all samples.

Mercury was only detected in the clay fraction, although heavy mineral concentrate data (see below) indicates many samples have significant quantities of cinnabar grains. In the clay fraction, Hg ranges from 0.02 to 1.0 ppm (average = 0.29 ±0.13 ppm). In the cumulative frequency plot there are no major breaks in slope, consistent with a close to normal distribution (Figure 3a). Setting the threshold at the 95th percentile (0.51 ppm), anomalous Hg contents occur in the west-central portion of the study area (Figure 4f), north of the two known Hg showings. Several till samples are also anomalous in Hg in the areas with Au, As and Ag anomalies in the northeastern and northwestern parts of the study area. Mercury values do not, however, correlate well with Au values (r = 0.083), but do correlate moderately with As values (r = 0.360).

Cu, Mo and Sb Contents

Copper was analyzed only for the clay fraction samples and ranges from 33 to 408 ppm (average = 125 ±38 ppm). Based on the cumulative probability plot, Cu contents in the clay fraction are anomalous at the 90th percentile (165 ppm; Figure 3a). Anomalous Cu contents occur in the northwestern corner of the study area, with smaller anomalies in the northeastern corner (Figure 4g). There is a positive concentration correlation between Cu and a number of other analytes such as Fe (r = 0.712), Sc (r = 0.654), V (r = 0.656), As (r = 0.538), Au (r = 0.410), Co (r = 0.341) and Mo (r = 0.313). These element associations indicate that Cu in the clay fraction of the till in the northwestern and northeastern parts of the study area is associated with Cu-Au mineralization.

Molybdenum was analyzed for both size fractions. All clay samples returned Mo contents above the detection limit, ranging from 0.3 to 12 ppm (average = 1.74 ±1.12 ppm). By contrast, the clay+silt fraction had only 132 samples above detection limit (1 ppm), ranging from 3 to 28 ppm. For the clay fraction, the anomalous threshold is around the 97th percentile (3.5 ppm; Figure 3a), whereas for the clay+silt fraction, all samples with detectable Mo can be considered anomalous at the 85th percentile (≥3 ppm; Figure 3a). The two size fractions show different spatial relationships. For the clay fraction, anomalous Mo contents occur mainly in the northeastern section of the study area; Mo contents are not anomalous in the northwestern section (Figure 4h). The highest Mo content is for a sample in the west-central part of the study area. By contrast, the clay+silt fraction has anomalous Mo contents scattered over much of the study area, with the most consistently elevated contents in the east-central and southern areas. Notably, Mo contents in the clay+silt fraction are below detection for the northwestern area where high Cu, Au and As values occur.

Antimony was measured for both size fractions, with clay contents ranging from 0.1 to 5.6 ppm (average = 0.80 ±0.48 ppm), and clay+silt contents ranging from 0.5 to 13.1 ppm (average = 1.84 ±0.87 ppm). Threshold values are around the 95th percentile for both fractions, at 1.5 and 2.7 ppm for the clay and clay+silt fractions, respectively (Figure 3a). Spatially, the two size fractions show similar distributions, with the most anomalous contents occurring in the northeastern section of the study area (Figure 4i).

Pb, Bi, Zn and Cd Contents

Lead was only analyzed in the clay fraction, and ranges from 6.6 to 64 ppm (average = 14.7 ±5.2 ppm). Lead shows a near normal distribution, although there is a subtle inflection in the cumulative probability plot near the 85th percentile (Figure 3a); setting the threshold value at the 95th percentile gives anomalous Pb at >24 ppm. The strongest correlations with Pb are shown by K (r = 0.591), La (r = 0.501), Bi (r = 0.668), Th (r = 0.720) and U (r = 0.621). The spatial distribution of anomalous Pb concentrations is distinct from the other ore-related elements, with the highest Pb contents in the north-central part of the map area, between the northeastern and northwestern areas that are anomalous in Au, Cu and As (Figure 4j). Bismuth (Figure 4k) shows a similar spatial distribution to Pb, along with U, Th and the rare earth elements (REE). Bismuth ranges from less than detection (0.1 ppm) to 2.7 ppm (average = 0.33 ±0.26 ppm), with a threshold around the 95th percentile (0.8 ppm; Figure 3b).

Zinc contents were analyzed in both size fractions and Cd was only analyzed in the clay fraction. Zinc contents in clay range from 83 to 531 ppm (average = 185 ±42 ppm) compared to 60 to 400 ppm in clay+silt (average = 167 ±49 ppm, with around 280 samples below detection). Cadmium shows similar spatial distribution to Zn, and ranges from 0.1 to 4.0 ppm (average = 0.75 ± 0.48 ppm). Both metals show the largest anomalies (threshold at the 95th percentile = 245 ppm Zn for clay, 250 ppm Zn for clay+silt and 1.6 ppm Cd for clay; Figure 3b) along the eastern side of the map area (Figure 4l, m), although Cd also shows several anomalous values in the west-central portion of the study area. Both Zn and Cd have strong positive correlations with Mo (r = 0.743 and 0.586, respectively), As (r = 0.421 and 0.364, respectively) and Sb (r = 0.464 and 0.334, respectively), as well as with each other (r = 0.719). Although Zn correlates poorly with major elements, Cd is strongly correlated with Ca (r = 0.595).

Rare Earth Elements, U, Th, K, Ca, Mg, Na, Cr, Hf, Co, Mn and Ni Contents

REE (La, Ce, Nd, Sm, Eu, Yb), U, Th, K, Ca, Mg, Na, Ni and Cr broadly show spatial relationships that are consistent with changes in the dominant underlying bedrock lithology (e.g., Figure 4n). Thus incompatible elements (i.e., REE, U, Th, K, Hf), which are usually associated with mafic alkalic rocks, are elevated in the northern part of the study area where mafic alkalic rocks occur. In the large HMC samples from this area of the map, >33% of the clasts that are >2 mm are granitoid, indicating a greater prevalence of alkalic volcanic rocks and associated late-stage intrusive rocks. Conversely, whereas Co shows a strong correlation with Mn in the clay fraction, Cr and Ni, which are strongly adsorbed by Mn oxides and oxyhydroxides (Nicholson and Eley, 1997; Leybourne et al., 2003), show distribution patterns that follow the major mafic volcanic bedrock units in the southern part of the study area (Figure 4n).

Heavy Mineral Concentrates: Au, Pyrite and HgS

All till samples processed for heavy minerals (n = 122) contain visible Au. The number of Au grains per ~10 kg of sample ranges from 1 to 91 (Figure 5a) and the calculated Au contents range from 1 to 4883 ppb (Figure 5b). Gold grains were classified on the basis of size and morphology. Gold grain morphologies are subdivided into three groups: pristine, modified and reshaped, based on the classification scheme of Dilabio (1990). The majority of Au grains in this study are classified as reshaped (1098 of a total of 1347 grains or 81.5%), with less common modified grains (15%) and rare pristine grains (3.5%). The threshold value for the total number of Au grains is around 12 to 15 (80–85th percentile), based on changes in slope of a probability distribution.

Although they are only estimates, grain counts of pyrite and cinnabar are useful. Pyrite counts range from zero to a high of ~10 000 grains. Most of the till samples with elevated pyrite grain counts (where anomalous values are approximately >50 grains) occur in the eastern and southern parts of the study area (Figure 5c), distinctly south of the area with anomalous metal values (northeastern corner of the study area; Figures 4a–i, k–m). By contrast, cinnabar counts range from 0 to 400, with anomalous cinnabar grain counts (approximately >60 grains) in the western part of the study area, with a trend of decreasing values to the southeast (Figure 5d).

Till Geochemical Exploration

Epigenetic Au-Cu Mineralization

In the northeastern part of the study area, there are a number of Au and Cu-Au showings, as well as two small past-producing placer deposits (discussed previously). Gold recovered from the placer deposits was described as wiry to angular (MINFILE 093J 007), suggesting that the placer gold had not been transported far from source. Samples of the clay fraction were analyzed by aqua-regia digestion followed by ICP-MS, whereas the silt+clay fraction was analyzed by INAA, thus the ICP-MS results will be less biased by the nugget effect. Gold in the clay fraction occurs either as clay-sized gold grains, most likely a result of glacial comminution and/or small-scale hydromorphic gold dispersion and adsorption to clay and oxyhydroxide mineral surfaces in the clay fraction. Other than a small number (~3) of highly anomalous Au values in the ICP-MS results, there is a relatively strong correlation (r = 0.410) between Cu and Au; this suggests that much of the Au is associated with Cu-sulphide minerals. The pathfinder elemental associations determined here (Sb, As, Se, Tl, Cd, Zn) are consistent with this style of mineralization. This association is coherent with descriptions of many of the showings in the northeastern section of the study area; showings of quartz veins with Cu±Au, Ag and/or PGE (MINFILE 093J 007, 093J 012, 093J 027, 093J 037), likely of epigenetic origin. The main cluster of till samples with anomalous values is essentially spatially coincident with many of the showings. The dominant ice flow towards the northeast can be used for further prospecting.

Porphyry Cu-Au

There is potential for porphyry Cu-Au–style mineralization in the study area based on the presence of the Mount Milligan porphyry Cu-Au developed prospect in correlative rocks to the northwest of the study area. The till geochemical data shows elevated values of Cu and Au and a number of pathfinder elements (e.g., As, Hg, Sb) in the northwestern part of the study area (Figures 4a, b, c, d, f, g, i). These anomalous till samples strongly indicate sources of mineralization up-ice, towards the southwest. There are a number of Cu and Cu-Au showings coincident and up-ice of this area of elevated geochemical values (Figure 2). At the Tsil showing (MINFILE 094C 180), in the northwestern corner of the study area, there are reports of outcrops of intermediate hornblende and feldspar porphyritic rocks exhibiting quartz-carbonate alteration with pyrite, pyrrhotite and rare chalcopyrite veins. The main cluster of Cu and Au anomalies in the northwestern part of the study area directly overlie the main cluster of Cu and Au showings in this area (Figure 2).

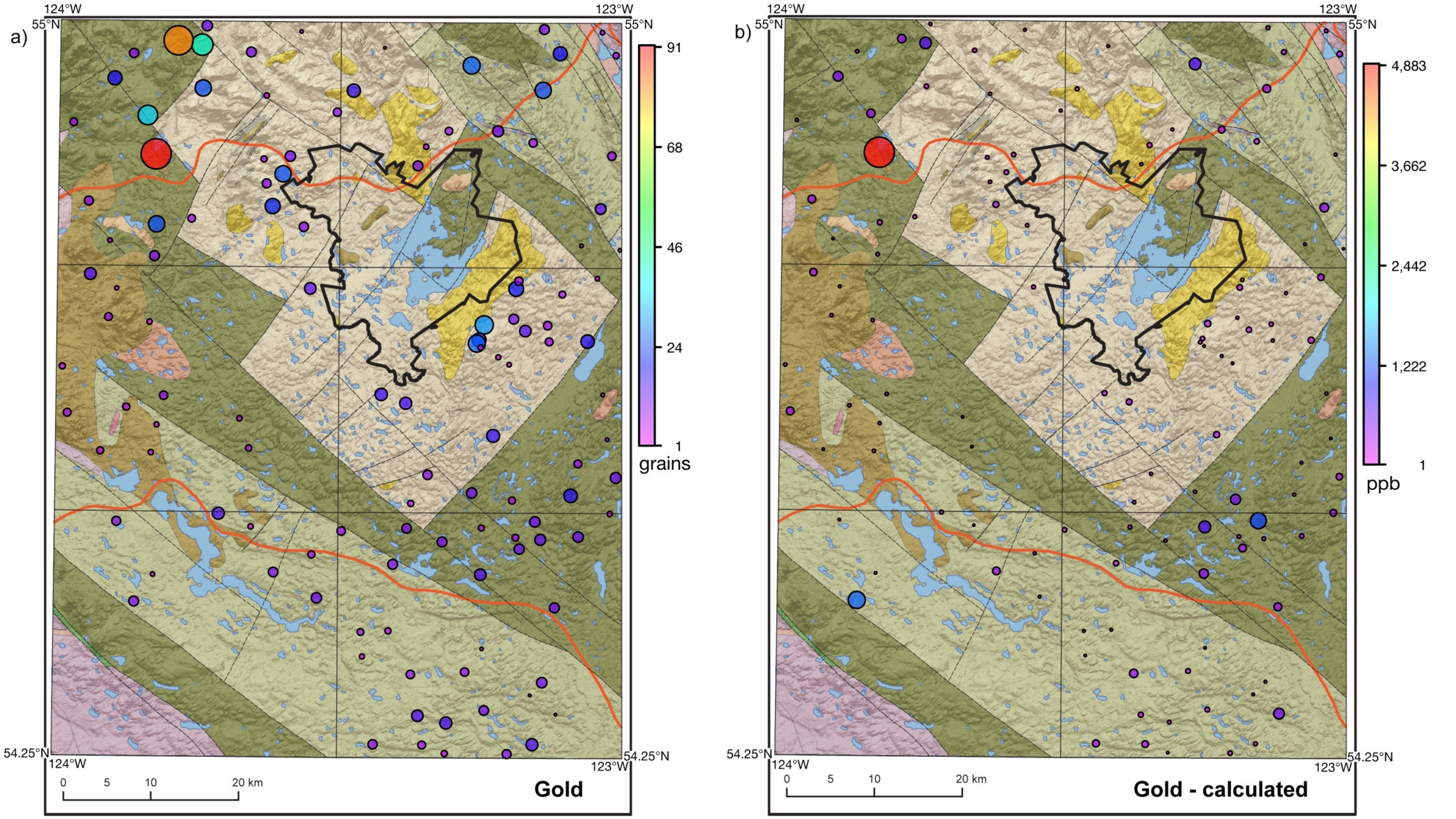

Figure 5. Proportional dot maps for **a)** gold grain counts from heavy mineral concentrates from 10 kg till samples, central British Columbia. Also presented are **b)** calculated gold contents (ppb) of heavy mineral concentrates, which are based on gold grain counts. Data are overlaid on the bedrock geology map presented in Figure 2.

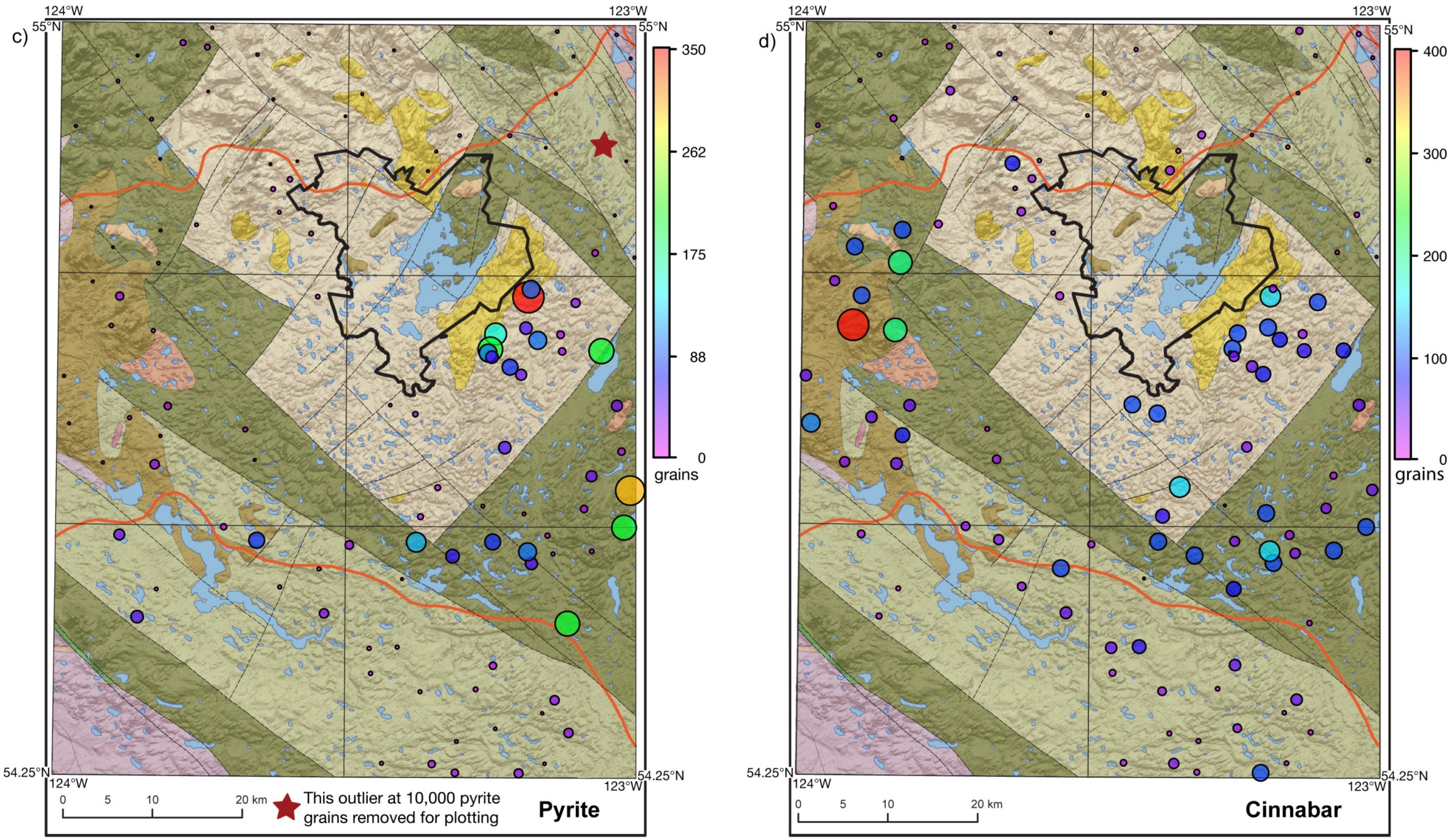

Figure 5 (continued). Proportional dot maps for **c)** pyrite and **d)** cinnabar grain counts from heavy mineral concentrates from 10 kg till samples, central British Columbia. Data are overlaid on the bedrock geology map presented in Figure 2.

Volcanogenic Massive Sulphide Deposits

VMS deposits occur to the southeast and to the northwest of the study area along the trend of the major bedrock units. There should be significant potential for VMS mineralization in the study area, even though there are no VMS showings or deposits listed in MINFILE. However, this study indicates there is relatively little spatial correlation between the major metals associated with VMS mineralization. Lead anomalies are clearly distinct from both Cu and Zn. The relatively low Pb contents in the till in the study area, compared to other areas of VMS deposits (cf., Hall et al., 2003; Parkhill and Doiron, 2003), could be related to three factors:

- Given the preponderance of mafic volcanic rocks in this part of BC, VMS mineralization, if present, would likely be lead-poor given the generally juvenile nature of the source of the volcanic rocks (Smith et al., 1995; Patchett and Gehrels, 1998; Dostal et al., 1999; Erdmer et al., 2002; Ross et al., 2005). Also, VMS deposits associated with ocean floor and oceanic arc settings are lead-poor compared to those associated with continental margins (Franklin et al., 1981; Galley et al., 2007).
- Only the clay fraction was analyzed for Pb, by aqua-regia digestion followed by ICP-MS, and it is possible that Pb is present in a less labile form or in a coarser size fraction.
- It is possible that the thick till units of the study area have diluted the geochemical signature of underlying bedrock lithologies resulting in subdued anomalies for metals.

There is still potential for VMS-style mineralization in the study area. The general lack of spatial correlation between anomalous Cu and Zn may simply be a function of VMS-related Cu anomalies being masked by greater Cu abundances associated with porphyry Cu-Au and epigenetic Au-Cu mineralization. Zinc shows poor correlations with Ni, Cr and Mg indicating that anomalous Zn contents in the till are not simply a function of weathering of mafic volcanic rocks. In addition to anomalous Zn along the eastern portion of the study area (Figure 4l), there are coincident anomalies for Cd, Bi and Tl, suggesting the potential for concealed, presently unrecognized, Zn mineralization. The HMC samples with the highest pyrite grain counts are also from the east-central part of the map area (Figure 5c), further suggesting the presence of VMS-style mineralization in this area. More detailed work following up the source of anomalous pyrite grain counts and Zn, Cd, Bi and Tl contents in the till is warranted.

Mercury

Pinchi Lake mercury mine (MINFILE 093K 049) is located on the Pinchi fault approximately 45 km to the northwest of the two Hg occurrences in the southwestern portion of the study area (Figure 2). The Pinchi Lake mine operated from 1940 to 1944 and 1968 to 1975, and was one of only two mercury-producing mines in Canada (Plouffe, 1998). The two Hg showings within the study area are associated with the extension of the Pinchi fault, but anomalous cinnabar counts and Hg contents in the clay fraction are not spatially associated with these showings (Figures 4f, 5d). Elevated cinnabar grain counts occur to the north of the showings, suggesting additional sources of fault-associated Hg mineralization up-ice from the cinnabar grains. Moderately elevated Hg in the clay fraction also occurs in the area of high cinnabar grain counts. Follow-up work that includes an analysis of the clay+silt fraction using an analytical method with lower detection limits for Hg is warranted.

Cluster Analysis

A k-means cluster analysis was performed on the geochemical results from the clay fraction of the till samples (Figure 6). Cluster analysis helps to identify natural groupings of geochemical data that may not be easily evident from manual identification (cf., Grunsky, 2010). It is a way of seeing elemental associations in a spatial context. K-means clustering is a method of partitioning n observations into k clusters, based on minimizing the sum of the squares from the mean within each cluster, similar to principle component analysis. In this analysis, data clusters are plotted as colour symbols for two, three, five and seven clusters; k-means cluster analysis requires independent estimates of the number of clusters. The k-means clustering was performed using the following elements: Mo, Cu, Pb, Zn, Ni, Co, Mn, Fe, As, U, Au, Sr, Cd, Sb, V, Th, Ca, La, Cr, Mg, Ba, Al, Na, K, Sc and Hg. These analyses graphically demonstrate the spatial associations described above and reflect differences in the bedrock geology and their potential styles of mineralization. Two clusters broadly divides the study area into a northern third and a southern two-thirds. This two cluster subdivision correlates well with the till samples in the north having higher Cu, Au, As, Hg, Sb, Ti, V, Hf, REE, U, Th and Pb (blue squares, Figure 6a) and till samples in the southern two-thirds having higher Ca, Mg, Cr and Ni (green diamonds, Figure 6a). As the number of clusters is increased, there is an increase in coherent data clusters that correspond to many of the element relationships, and potential styles of mineralization, discussed above. Thus, for five and seven clusters (Figures 6c, d), the analysis clearly separate tills in northwestern part of the study area that are elevated in Cu-Au (green diamonds, Figure 6c; solid blue squares, Figure 6d), from tills of the northeastern part that are elevated in Cu-Au-Mo-Ag-Sb (pink crosses, Figure 6c; red diamonds, Figure 6d). Both of these areas are distinct from the region between them, which is characterized by anomalous Pb and Bi contents in the till (blue open squares, Figure 6c; red crosses, Figure 6d). The seven-cluster plot also distinguishes the very southern block of till

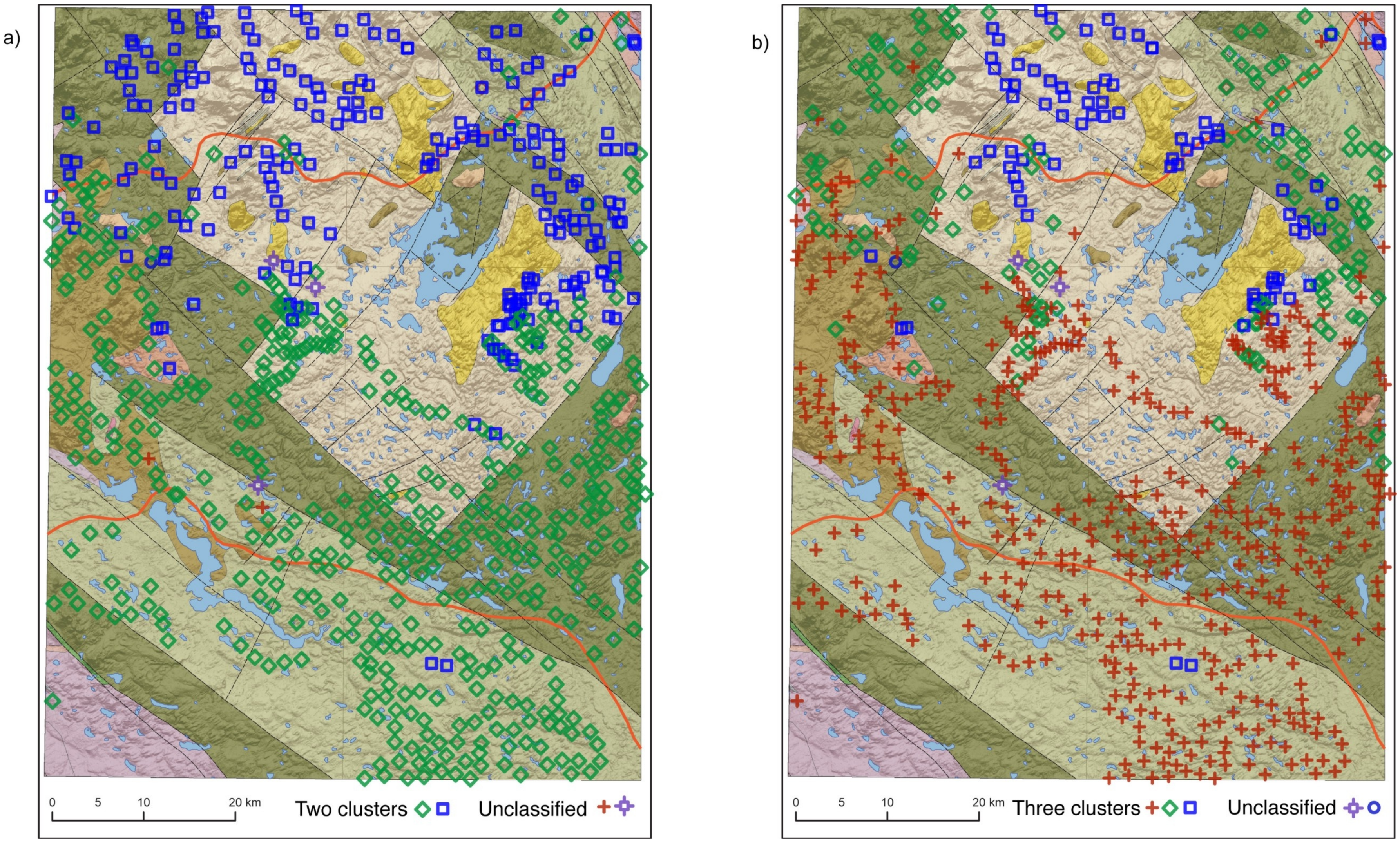

Figure 6. Results of cluster analysis of the clay fraction of till geochemical data (Mo, Cu, Pb, Zn, Ni, Co, Mn, Fe, As, U, Au, Sr, Cd, Sb, V, Th, Ca, La, Cr, Mg, Ba, Al, Na, K, Sc and Hg), central British Columbia. Samples were divided into **a)** two and **b)** three clusters. Data are overlaid on the bedrock geology map presented in Figure 2. Note that although the number of clusters is set for each analysis, data that do not conform to a major cluster are assigned different symbols.

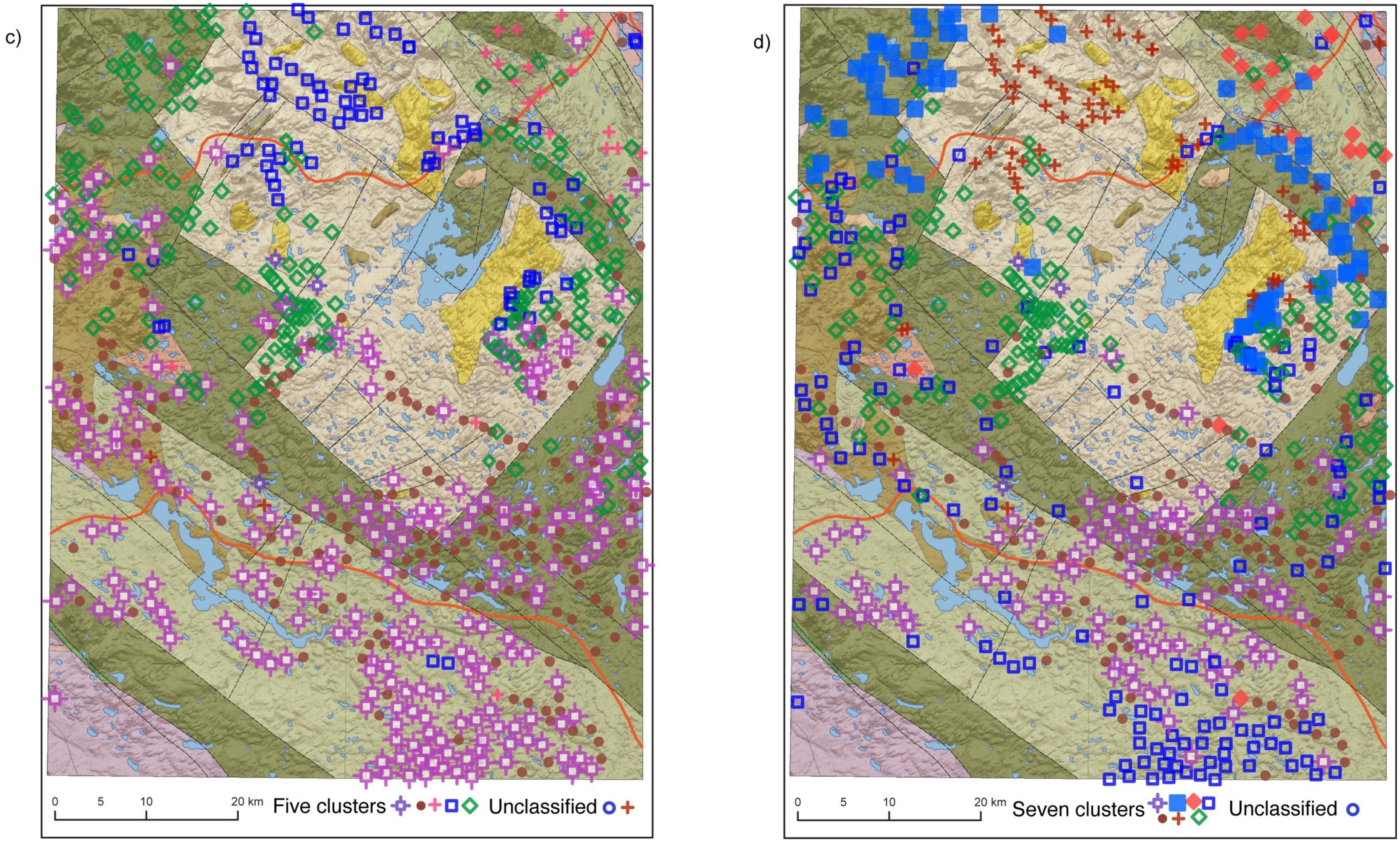

Figure 6 (continued). Results of cluster analysis of the clay fraction of till geochemical data (Mo, Cu, Pb, Zn, Ni, Co, Mn, Fe, As, U, Au, Sr, Cd, Sb, V, Th, Ca, La, Cr, Mg, Ba, Al, Na, K, Sc and Hg), central British Columbia. Samples were divided into **c)** five and **d)** seven clusters. Data are overlaid on the bedrock geology map presented in Figure 2. Note that although the number of clusters is set for each analysis, data that do not conform to a major cluster are assigned different symbols.

samples (open blue squares), from the other southern till (purple box crosses), based on the most southern group having less elevated Cr, Ni and Mg contents (Figure 6d).

Conclusions

In part of the QUEST Project area, central BC, 712 till samples have been collected where thick glacial deposits cover bedrock, hindering both bedrock mapping and mineral exploration programs. The study area occurs within the Quesnel terrane, and is dominated by middle to upper Triassic mafic volcanic rocks and volcaniclastic sedimentary rocks of the Nicola Group. The large Mount Milligan Cu-Au porphyry deposit occurs just to the northwest of the study area in correlative rocks, part of a near linear, northwest-trending series of Cu±Mo deposits that occur within this terrane. Till geochemical data and heavy mineral grain count data highlight four areas that warrant further work:

1) In the northwestern part of the study area, there is a large number of till samples with significantly anomalous Cu and Au contents (and coincident but less significant As and Ag anomalies). The underlying rocks are correlative with those that host the Mount Milligan Cu-Au porphyry deposit. Consistent with the potential for porphyry Cu-Au style mineralization, there are a number of showings associated with alkalic volcanic and porphyritic rocks. This area also has elevated Hf, REE, Th, Ti, Fe and V, reflecting Fe-rich alkalic igneous rocks in the underlying and up-ice bedrock.
2) In the northeastern part of the study area, there are Au, Cu, As, Ag, Sb and Cd anomalies in an area with several epigenetic-type Cu-Au vein showings and two small-scale past-producing Au (and Pt) placer mines.
3) In the east-central portion of the study area, till samples have elevated Zn, Cd and Bi contents, as well as high pyrite grain counts (up to 10 000 grains in a 10 kg sample). There are no known showings or mineralization in this part of the study area; the till geochemical results suggest the possibility of concealed VMS-type mineralization.
4) In the west-central portion and into the central portion of the study area, Hg values and elevated cinnabar grain counts suggest there is fault-associated Hg mineralization up-ice, perhaps similar to the Pinchi Lake mercury mine located to the west of the study area.

In these four areas, increased till sample density could provide some insight into the locations of potentially mineralized bedrock. Till sampling can become more challenging, however, as sample density increases appropriate sample material can be difficult to find and access to good sample sites can be limited. In such cases, prospecting (including an examination of clasts in drift) and trenching could be carried out to further test these areas.

Acknowledgments

Geoscience BC provided the majority of funding for this project and the authors extend many thanks to C. Anglin and C. Sluggett for helping to make this project happen. The Mountain Pine Beetle (MPB) Program under the direction of C. Hutton (GSC, Natural Resources Canada) provided funding for a portion of the geochemical analyses for samples taken in 2008. M. Casola, M. Dinsdale, K. Kennedy, J. McDonald, C. Pennimpede, S. Reichheld, I. Sellers and D. Vis provided able assistance in the field. Geochemical reference standards were provided by R.E. Lett, along with helpful discussion on till geochemistry with the first author. Review by T. Ferbey improved the manuscript. J. Dawson spent an inordinate amount of time improving the clarity of the manuscript.

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