

Soil and till geochemical surveys at the Ace mineral property, central British Columbia



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Abstract

A multi-media surficial geochemical survey was carried out by the British Columbia Geological Survey in 2000 to document the geochemical expression of massive sulphide and gold-quartz vein mineralization at the Ace mineral property, near Likely. Much of the bedrock on the property is concealed by lodgement (basal) till, which was deposited by a southeast to northwest ice advance, ablation till, and colluvium. Soil samples from the B-horizon soil and transitional B-C horizon, and lodgement till were collected from 85 sites and the <0.063 mm (-230 mesh fraction) was analyzed for more than 50 minor and trace elements and major oxides by three methods: modified aqua regia dissolution-inductively coupled plasma mass spectrometry; instrumental neutron activation; and lithium metaborate fusion-inductively coupled plasma emission spectroscopy. Samples were also analyzed for carbon, sulphur, and loss on ignition. Five size fractions ranging from 1-2 mm to 0.125-0.063 mm of selected till and soil samples were analyzed for 35 trace elements by modified aqua regia dissolution followed by ICP-MS.

The commodity and pathfinder metals Au, As, Bi, Co, Cu, Pb, Se, and Zn are present in higher concentrations in the <0.063 mm fraction of the basal till than in the B-horizon soil, likely because the metal content in the silt- and clay-sized fraction of till more closely reflects the chemistry of bedrock after comminution and dispersal. However, Ag and Hg have higher concentrations in the B-horizon soil where they were likely captured and concentrated by organic matter during soil formation. Till and soil size fraction analysis for metals show that Au and Pb are present in soil and till as discrete mineral grains larger than 0.063 mm. Anomalous Co, Cu, Pb, Se, and Zn concentrations in till and soil define a ribbon-shaped dispersal train along the northern edge of the survey area. The train formed from glacial erosion of mineralized bedrock, that was then transported and deposited by an east to west ice flow. This train was then subjected to post-glacial modification by colluvial processes. The trace element dispersal profiles suggest a massive sulphide source for the anomalous metals in bedrock beneath the till at the east end of the dispersal train. Potentially, other till and soil Au and As anomalies in the western and southern parts of the survey area could have been derived from unmapped, northeast-trending Au-quartz veins.

Keywords: Surficial geochemistry, till, B-horizon soil, Ace property, ICP-MS, drift prospecting

1. Introduction

Dispersal trains of minerals and rock debris in glacial sediment have long-been used to detect mineralized bedrock beneath glacially transported sediments, and the application of this concept has resulted in many successful till geochemical surveys in Canada (e.g., Hickin and Plouffe, 2017; McClenaghan and Paulen, 2018). In British Columbia, several examples have documented till geochemistry patterns related to a known mineralized bedrock source: Mount Milligan (Sibbick et al., 1996); Samatsum Mountain (Paulen, 2001); Bell Copper (Levson, 2001, 2002); Huckleberry (Ferbey and Levson, 2009; Ferbey et al., 2012); Mount Polley (Hashmi et al., 2015); and Blackwater Davidson (O'Brien et al., 1997; Averill, 2017).

Geochemical soil surveys (i.e., B-horizon soil samples) are still commonly used in for mineral exploration in British Columbia because they are faster and less labour intensive than till sampling. However, in glaciated terrain soil survey results can be misleading because the geochemical anomalies at surface typically do not overlie mineralization. Instead

anomalies reflect metal-rich till that was displaced down-ice from a bedrock source. Chemical processes are largely responsible for element dispersion in soil whereas in till, the dispersal mechanism is mechanical. Soils are also subject to other surficial post-glacial modifications such as colluvial processes, which have been shown to deform and alter the surface geometry of dispersal trains (Paulen, 2001). Numerous studies have been carried out in British Columbia to better understand the complex relationship between soil and till geochemistry and mineralized bedrock such as in the Babine porphyry copper belt (Levson, 2002), over the Galaxy property near Kamloops (Kerr et al., 1993; Lett, 2010), in the Adams Lake area (Lett, 2001) and at Mouse Mountain (Lett, 2009).

This paper describes B-horizon soil and C-horizon glacial sediment sampling on the Ace mineral property (BC MINFILE 093A 142) in the east Cariboo Lake area of central British Columbia (Fig. 1) to establish relationships between the soil and till geochemistry in an area where bedrock is mainly concealed by lodgement till, ablation till, and colluvium. The Ace mineral

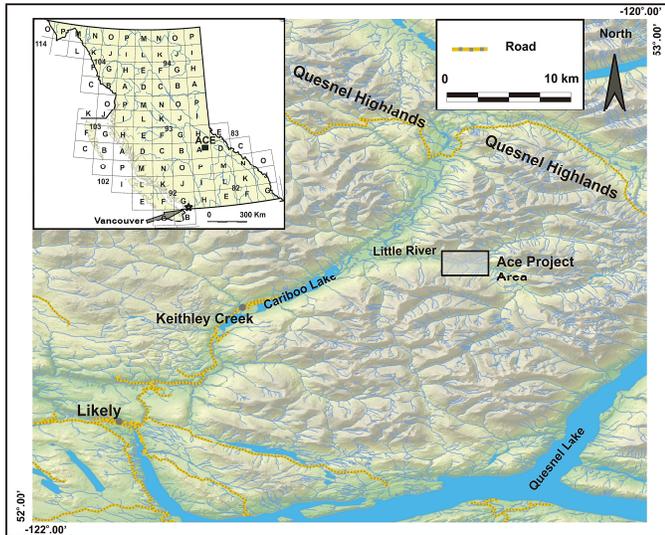


Fig. 1. Ace project location.

property was discovered in 1993 by Mr. Louis Doyle who identified gold grains in sediment panned from a creek flowing through the area. Subsequent prospecting revealed a sulphide-mineralized boulder train crossing the property for several km. Since 1993, mineral exploration identified evidence of base metal massive sulphide mineralization and gold-quartz sulphide veins hosted by Paleozoic metasedimentary and metavolcanic rocks of the Snowshoe Group (Höy and Ferri, 1998). In 2000, a detailed soil and glacial sediment sampling program directed by Peter Bobrowsky, collected 97 till and 81 B and B-C soil horizon samples from 85 sites (Bichler and Bobrowsky, 2000; Lett et al., 2005). This paper describes and presents interpretations of the soil and till geochemistry for the commodity and pathfinder elements Ag, Au, As, Cu, Co, Pb, Se, and Zn.

2. Survey area description

2.1. Physiography

The Ace property is in the Quesnel Highland, a physiographic subdivision of the Interior Plateau (Fig. 1; Holland, 1976). The property is accessible along gravel roads from the village of Likely, 34 km to the southwest. Topography reflects the erosion of a highly dissected plateau with a moderate relief. The area is drained by the Little River and its tributaries, which flow west into Cariboo Lake. Most of the sampling sites are on a glaciated, northeast-facing valley slope between a ridge to the south and the steep walled Little River valley to the north. Forest canopy species include White spruce, sub-alpine fir, Douglas fir, Lodgepole pine, and aspen with an understory of Devils Club, alder and blackberry. Depending on the surface environment and site drainage, organic, luvisolic, podzolic or brunisolic soils have formed on the glacial deposits.

2.2. Surficial geology

The region is blanketed by glacial sediments deposited by the Late Wisconsin Cordilleran Ice Sheet with local post-

glacial modification by Holocene colluvial processes (Bichler and Bobrowsky, 2000). Ice-flow indicators in the region surrounding the Ace property are shown in Figure 2. The limits and extent of a mineralized boulder field in the Ace study area was mapped by Bicher and Bobrowsky (2000); glacial deposit samples included basal till and ablation till (Fig. 3). The basal till has been reworked into colluvium on the steeper slopes of the Little River valley. Ablation till, identified at three sample sites to the south-east of the boulder field, may reflect englacial or supraglacial sediment deposited in the Little River valley during retreat of the ice sheet. Basal till was deposited by ice that flowed from the Cariboo Mountains towards the northwest. One ice-flow measurement of 165° (P. Bobrowsky, pers. comm., 2000) indicates that ice advanced from the southeast to northwest parallel to the Little River valley.

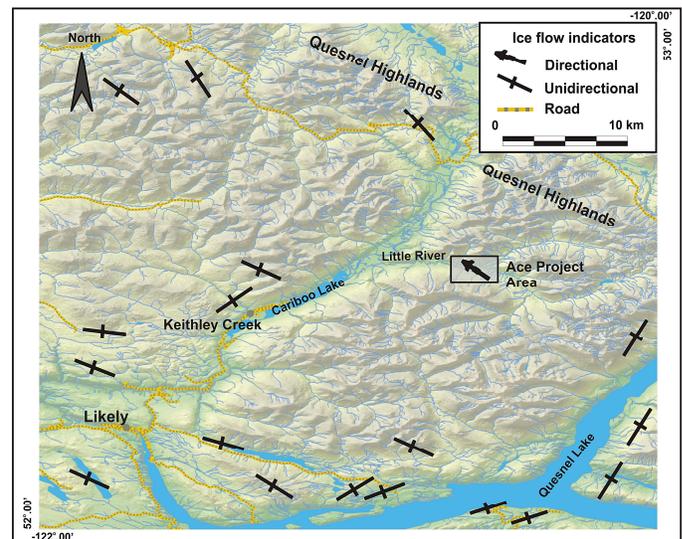


Fig. 2. Regional ice-flow indicators in the area near the Ace property (after Arnold and Ferbey, 2020; Bobrowsky, pers. comm., 2000).

2.3. Bedrock geology and mineralization

Tan to pale grey or green and dark grey graphitic phyllite of the Snowshoe Downey succession (lower to middle Paleozoic) underlie the Ace property (Fig. 4). Höy and Ferri (1998) suggested that these phyllites originated as fine-grained sedimentary rocks, but that green, massive chloritic phyllites visible in trenches may be metamorphosed mafic volcanic rocks. Amphibolites outcropping on the hill slope south of the area sampled were interpreted by Höy and Ferri (1998) as diorites or possibly felsic volcanic rocks. North of the Little River, bedrock consists of limestone, black phyllite, and siltstone of the Snowshoe Bralco succession and predominantly quartzite and sandstone of the Cariboo Group (Ferri and O'Brien, 2002). The contact between the Cariboo Group and the Bralco succession is a thrust fault; this thrust is cut by two northeast-trending faults that extend into the Snowshoe Downey sedimentary rocks.

Massive sulphide bodies and gold hosted in quartz veins are two deposit types suspected to be present on the Ace property

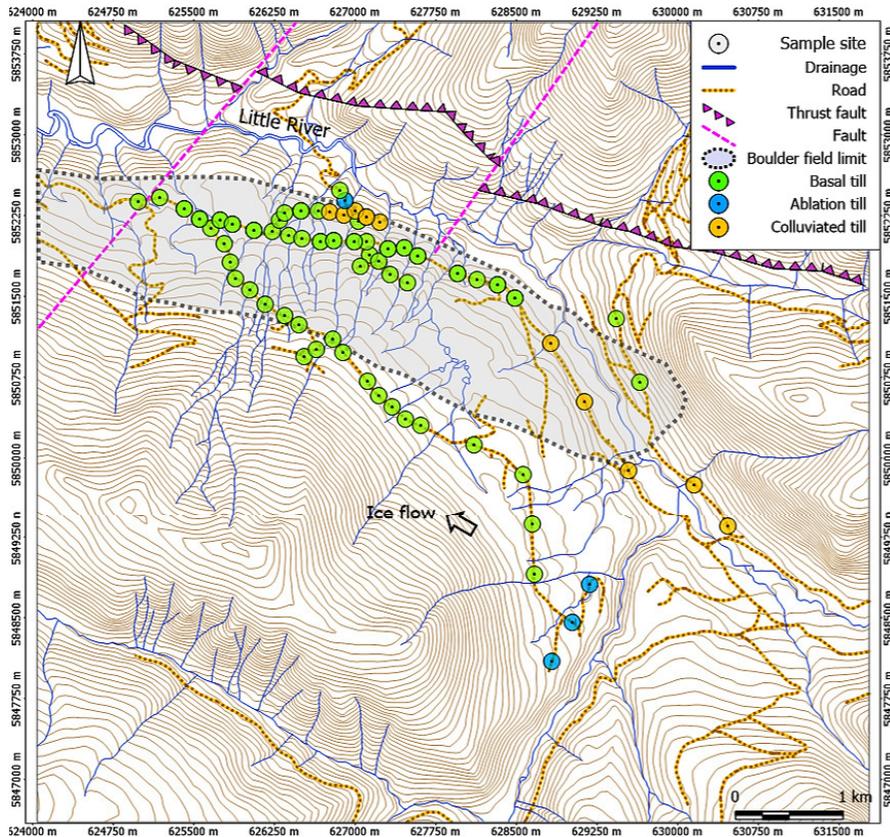


Fig. 3. Glacial sediment sample locations and types of sediment identified; extent of a mineralized boulder field from Bicher and Bobrowsky (2000).

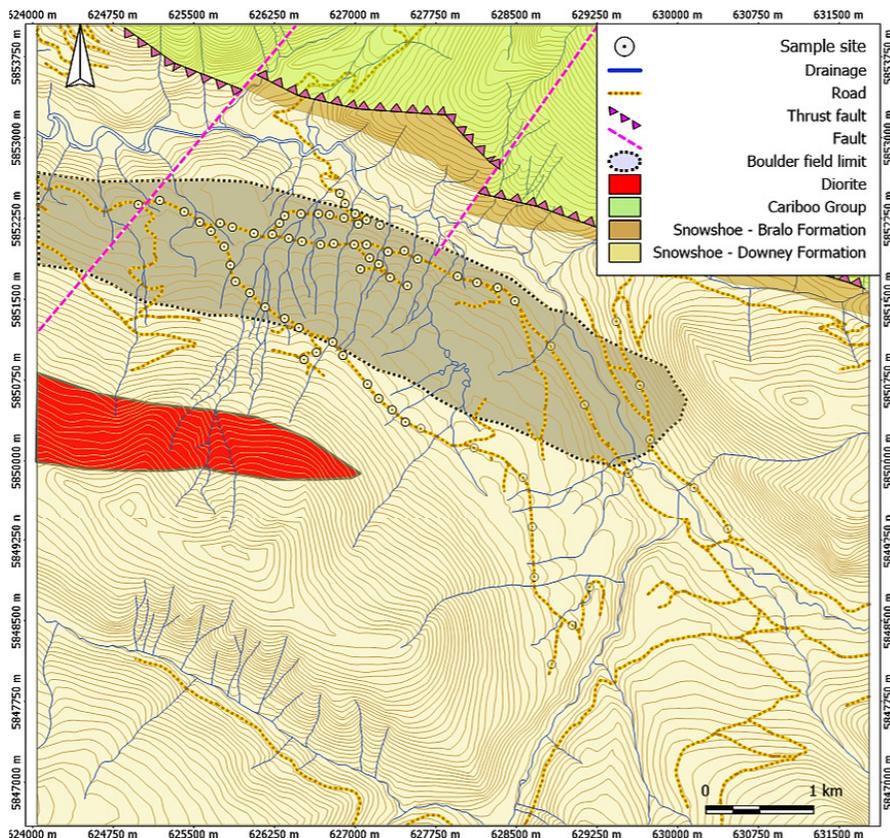


Fig. 4. Bedrock geology of the survey area (after Cui et al., 2017).

based on evidence from float samples, trench exposures, and outcrop. Massive pyrite and pyrrhotite form lenses up to 1.2 m thick in quartz-feldspar-muscovite-chlorite-biotite-garnet schists and 'felsite' interbeds (BC MINFILE 093A 142). Chalcopyrite and sphalerite have also been reported in bedrock and boulders (Höy and Ferri, 1998), but sulphide concentrations are typically less than one percent. Höy and Ferri (1998) interpreted the mineralization to be Besshi-type (Cu-Zn) volcanic massive sulphide (VMS). In addition to the massive sulphides, Au-bearing quartz veins have also been identified on the property, folded within and cross cutting the phyllites (Höy and Ferri, 1998). The veins contain native Au, cubanite, native bismuth, and tourmaline. Geochemical analysis of the vein rock shows elevated Fe, As, Au, Ag, Zn, Cu, Bi, and Te concentrations (Höy and Ferri, 1998).

3. Sampling, sample preparation, and analysis

Soil and the parent glacial sediment (i.e., till) were collected on the Ace property at sites between 150 to 200 m apart along the roads using a small backhoe excavator to dig a trench one m wide and several m deep (Fig. 5). After fully describing the soils and the tills upon which they were developed, samples of the B-horizon soil (0.1 to 0.6 m; mean depth 0.28 m), transition from B to C (B-C) horizon (0.2 to 1.1 m mean depth 0.61 m), and C-horizon (0.6 to 3.2 m; mean depth 1.34 m) were described and collected from the trenches for analysis at each

site. Bondar and Clegg Laboratories, North Vancouver, air dried the samples and split them into two sub-samples. One sub-sample was sieved to <0.063 mm grain size (-230 mesh) and the second sub-sample was retained as a character sample. The samples were returned to the British Columbia Geological Survey laboratory in Victoria, for addition of quality control samples before analysis at commercial laboratories.

A 0.5 gram aliquot of the <0.063 mm fraction of each sample was analyzed by Acme Analytical Laboratories Ltd., (now Bureau Veritas) Vancouver, for 37 elements including Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Ni, Pb, Se, Tl, and Zn by a modified aqua regia digestion (1:1:1 solution of HNO₃-HCl-H₂O acids) and a combination of inductively coupled plasma-mass spectrometry (ICP-MS) and inductively coupled plasma-emission spectroscopy (ICP-ES). A second aliquot of the <0.063 mm fraction (~30 g) was analyzed by Activation Laboratories, Ancaster, Ontario, by instrumental thermal neutron activation analysis (INAA) for Au and 32 elements.

Selected till and soil samples were also sieved into -10 to +18 mesh (1 to 2 mm); -18 to +35 mesh (0.5 to 1 mm); -35 to +60 mesh (0.250 to 0.5 mm); -60 to +120 mesh (0.125 to 0.250 mm) and -125 to -230 mesh (0.063 to 0.125 mm) size fraction. Samples of each of the fractions were analyzed for 37 elements including Ag, As, Au, Bi, Cd, Co, Cu, Fe, Hg, K, Mo, Ni, Pb, Sb, Se, Te, Tl, and Zn by modified aqua regia digestion (1:1:1

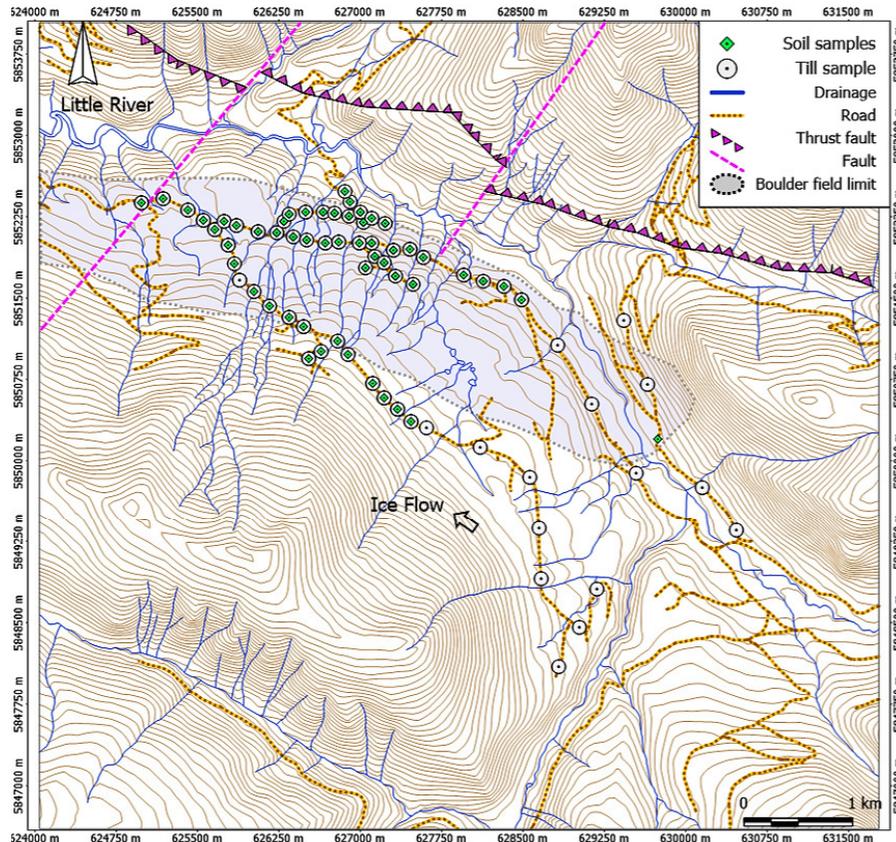


Fig. 5. Till and soil sample locations.

solution of HNO₃-HCl-H₂O acids) followed by ICP-MS/ES. This paper describes the geochemistry of 16 of the elements; the full dataset will be presented elsewhere (Lett and Paulen, 2021).

4. Quality control measures

No reliable interpretation of geochemical data is possible unless there is an estimate of the variability, expressed as precision, introduced by the sampling and by the sample analysis. Precision of the Ace geochemical data is estimated by statistical analysis of results from the analysis of sieved duplicate samples collected at field sites, sieved duplicates prepared in the laboratory, and randomly inserted standard reference materials. Table 1 lists detection limits, mean values, and percent relative standard deviation (% RSD) for Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Ni, Pb, Sb, Se, Te, Tl, and Zn in six samples of the British Columbia Geological Survey in-house standard (Till 99) that were analyzed by a modified aqua regia digestion followed by ICP-MS and for Au by INAA. Except for Au, the RSD is less than 15% and the precision is considered acceptable. The greater Au precision by INAA of 12.1%, as compared with 18.7% by aqua regia-ICP-MS, reflects the larger aliquot (typically 30 g) used for the INAA analysis.

An average coefficient of variation, or CV_{AVR}(%) calculated from a formula proposed by Abzalov (2008) provides an estimate of sampling precision from the field and laboratory duplicate data (Eqn. 1). In the formula, the terms a and b represent the analyses of the first and second of the duplicate sample pair

$$CV_{AVR}(\%) = 100 \times \sqrt{\frac{2}{N} \sum_{i=1}^N \frac{(a_i - b_i)^2}{(a_i + b_i)^2}} \quad \text{Eqn. 1}$$

and N is the number of duplicate pairs. Values can range from 0%, where duplicate pairs have identical concentrations, to an upper value above 141.21% (i.e., the square root of 2) where duplicate results exhibit maximum differences.

In Table 2, the CV_{AVR}(%) values for each element in the <0.063 mm fraction of 15 till-soil field duplicate sample pairs analyzed by aqua regia-ICP-MS/ES and Au by INAA are sorted in order of their increasing field duplicate CV_{AVR}(%) value (i.e., good to poor precision). Average coefficient of variation values below 15% (green) indicate good data quality, values between 15 and 30% (blue) acceptable quality, those over 30% (red) marginal to poor quality. Gold Se, Hg, Te, and Bi have marginal precision and the data for these elements should be interpreted with caution.

5. Summary statistics

Tables 3, 4, and 5 list minimum, mean, median, standard deviation (SD), 3rd quartile, 80th percentile, 90th percentile, 95th percentile and maximum values for trace elements in 97 till samples, 26 B-C horizon soil samples, and 55 B-horizon soil samples. Median and 3rd quartile values in the three tables reveal that the elements can: 1) decrease from the till through the B-C horizon to the B horizon; 2) remain essentially the same; or 3) decrease. Silver, Cd, and Mo are higher in the B-horizon soil compared with till, whereas Au, Cu, As, and Zn are higher in the till (Table 6).

Table 1. Detection limits (DL), mean values, and percent relative standards deviations from six analyses of the British Columbia Geological Survey standard Till 99 determined by modified aqua regia digestion-ICP-MS and Au by instrumental neutron activation (INAA).

Element	DL	Mean	Pct RSD
Ag ppb ICP	2	1351	4.3
As ppm ICP	0.1	57.5	8.1
Au ppb ICP	0.2	26.6	18.7
Au ppb INAA	2	33.40	12.1
Bi ppm ICP	0.02	0.25	2.0
Cd ppm ICP	0.01	0.67	8.5
Co ppm ICP	0.1	45.0	7.4
Cu ppm ICP	0.01	168.69	2.1
Hg ppb ICP	5	377	3.3
Mo ppm ICP	0.01	0.80	5.6
Ni ppm ICP	0.1	210.6	2.8
Pb ppm ICP	0.01	209.77	2.5
Sb ppm ICP	0.02	10.64	1.9
Se ppm ICP	0.1	0.8	13.3
Te ppm ICP	0.02	0.29	5.1
Tl ppm ICP	0.02	0.10	4.9
Zn ppm ICP	0.1	357.1	6.3

Table 2. Average coefficient of variation (CV_{AVR}(%)) calculated from the analysis of 15 till and B-horizon soil field duplicate samples analyzed for trace metals by modified aqua regia digestion-ICP-MS and for Au by instrumental neutron activation (INAA). The field duplicate CV_{AVR}(%) values are sorted by increasing size. Average coefficient of variation values below 15% (in green) indicate good data quality, values between 15 and 30% (in blue), are acceptable quality and values over 30% (in red) reflect marginal to poor data quality.

Element	Field Duplicate CV _{AVR} (%)	Analytical Duplicate CV _{AVR} (%)
Zn ppm ICP	5.0	2.7
Tl ppm ICP	5.4	3.6
Ni ppm ICP	7.6	4.2
Co ppm ICP	8.8	4.5
Pb ppm ICP	8.8	4.4
Mo ppm ICP	9.4	4.3
Cu ppm ICP	10.0	2.4
As ppm ICP	13.3	7.4
Se ppm ICP	15.1	36.7
Hg ppb ICP	18.1	25.5
Cd ppm ICP	21.2	14
Ag ppb ICP	22.2	6.4
Sb ppm ICP	23.3	34.9
Te ppm ICP	31.9	24.9
Bi ppm ICP	41.6	5.7
Au ppb ICP	49.7	48.4
Au ppb INAA	66.1	87

Table 3. Statistics for trace element data for 97 till samples analyzed by modified aqua regia digestion-ICP-MS and INAA (Au).

Element	Minimum	Mean	Median	SD	3rd Quartile	80 percentile	90 percentile	95 percentile	Maximum
Ag ppb ICP	4.00	60.92	42.00	62.08	77.00	83.40	113.00	179.60	460.00
As ppm ICP	1.10	9.34	3.50	14.91	6.70	8.94	24.02	53.42	69.60
Au ppb ICP	0.60	7.36	3.50	16.15	5.70	6.64	12.28	16.06	132.40
Au ppb INAA	1.00	6.02	1.00	10.01	8.00	9.80	16.00	22.00	74.00
Bi ppm ICP	0.23	1.28	0.89	1.51	1.28	1.36	1.92	3.07	10.54
Cd ppm ICP	0.01	0.21	0.10	0.25	0.22	0.29	0.58	0.79	1.26
Co ppm ICP	13.70	30.17	27.50	10.98	34.70	36.68	41.04	50.13	76.10
Cu ppm ICP	28.70	77.66	74.94	23.42	88.35	95.35	101.61	111.85	163.80
Hg ppb ICP	5.00	19.06	17.00	9.89	24.00	25.60	30.00	33.00	60.00
Mo ppm ICP	0.36	1.84	0.95	2.49	1.73	2.30	4.05	5.65	16.69
Ni ppm ICP	37.30	65.97	64.60	16.70	72.80	77.70	91.28	96.86	113.20
Pb ppm ICP	7.25	29.57	19.04	29.52	32.34	35.01	63.09	77.30	231.55
Sb ppm ICP	0.01	0.07	0.06	0.07	0.08	0.09	0.14	0.19	0.45
Se ppm ICP	0.05	0.54	0.40	0.41	0.80	0.90	1.10	1.20	1.90
Te ppm ICP	0.01	0.07	0.06	0.04	0.08	0.08	0.10	0.16	0.24
Tl ppm ICP	0.08	0.27	0.25	0.09	0.08	0.32	0.38	0.45	0.64
Zn ppm ICP	58.70	115.40	94.90	55.35	133.90	133.94	177.44	208.85	415.90

Table 4. Statistics for trace element data for 26 B-C soil horizon samples analyzed by modified aqua regia digestion-ICP-MS and INAA (Au).

Element	Minimum	Mean	Median	SD	3 Quartile	80 percentile	90 percentile	95 percentile	Maximum
Ag ppb ICP	28	224	188	141	281	298	400	495	665
As ppm ICP	1.30	6.07	3.30	11.35	5.10	5.22	7.96	17.82	79.90
Au ppb ICP	0.10	5.02	1.70	15.39	2.85	3.12	4.32	18.40	109.90
Au ppb INAA	1	3	1	4	1	4	10	14	16
Bi ppm ICP	0.33	1.01	0.76	1.20	1.09	1.15	1.56	1.97	9.06
Cd ppm ICP	0.03	0.21	0.17	0.14	0.27	0.29	0.40	0.45	0.67
Co ppm ICP	7.70	18.42	17.10	6.38	21.95	23.52	26.92	30.50	38.30
Cu ppm ICP	15.24	43.17	38.21	19.35	54.92	56.33	63.76	74.35	109.62
Hg ppb ICP	7	77	75	29	90	98	113	121	158
Mo ppm ICP	0.55	1.76	1.31	1.37	2.10	2.22	3.37	4.01	8.88
Ni ppm ICP	15.4	41.5	37.7	16.9	52.8	55.5	65.9	74.9	91.2
Pb ppm ICP	10.25	21.00	16.90	13.20	21.35	23.50	36.61	49.26	74.97
Sb ppm ICP	0.01	0.07	0.06	0.05	0.09	0.09	0.12	0.14	0.32
Se ppm ICP	0.1	0.6	0.6	0.2	0.7	0.8	1.0	1.1	1.2
Te ppm ICP	0.01	0.05	0.04	0.03	0.06	0.06	0.08	0.09	0.15
Tl ppm ICP	0.08	0.15	0.15	0.04	0.17	0.17	0.20	0.22	0.23
Zn ppm ICP	38.5	104.9	92.5	47.0	119.9	132.2	153.5	200.1	295.2

Table 5. Statistics for trace element data for 55 B-horizon soil samples analyzed by modified aqua regia digestion-ICP-MS and INAA (Au).

Element	Minimum	Mean	Median	SD	3 Quartile	80 percentile	90 percentile	95 percentile	Maximum
Ag ppb ICP	28	224	188	141	281	298	400	495	665
As ppm ICP	1.30	6.07	3.30	11.35	5.10	5.22	7.96	17.82	79.90
Au ppb ICP	0.10	5.02	1.70	15.39	2.85	3.12	4.32	18.40	109.90
Au ppb INAA	1	3	1	4	1	4	10	14	16
Bi ppm ICP	0.33	1.01	0.76	1.20	1.09	1.15	1.56	1.97	9.06
Cd ppm ICP	0.03	0.21	0.17	0.14	0.27	0.29	0.40	0.45	0.67
Co ppm ICP	7.70	18.42	17.10	6.38	21.95	23.52	26.92	30.50	38.30
Cu ppm ICP	15.24	43.17	38.21	19.35	54.92	56.33	63.76	74.35	109.62
Hg ppb ICP	7	77	75	29	90	98	113	121	158
Mo ppm ICP	0.55	1.76	1.31	1.37	2.10	2.22	3.37	4.01	8.88
Ni ppm ICP	15.4	41.5	37.7	16.9	52.8	55.5	65.9	74.9	91.2
Pb ppm ICP	10.25	21.00	16.90	13.20	21.35	23.50	36.61	49.26	74.97
Sb ppm ICP	0.01	0.07	0.06	0.05	0.09	0.09	0.12	0.14	0.32
Se ppm ICP	0.1	0.6	0.6	0.2	0.7	0.8	1.0	1.1	1.2
Te ppm ICP	0.01	0.05	0.04	0.03	0.06	0.06	0.08	0.09	0.15
Tl ppm ICP	0.08	0.15	0.15	0.04	0.17	0.17	0.20	0.22	0.23
Zn ppm ICP	38.5	104.9	92.5	47.0	119.9	132.2	153.5	200.1	295.2

Table 6. Element increase/decrease from till through BC soil horizon to B soil horizon based on 3rd quartile values listed in Tables 3 to 5. The increase/decrease is shown as a shaded bar; dark blue = high concentration, light blue = low concentration. Left side of plot is till, middle of plot is B-C soil horizon, right side of plot is B-horizon soil.

Element	Till	BC Soil Horizon	B Soil Horizon
Ag ppb ICP			
As ppm ICP			
Au ppb ICP			
Au ppb INAA			
Bi ppm ICP			
Cd ppm ICP			
Co ppm ICP			
Co ppm INAA			
Cu ppm ICP			
Hg ppb ICP			
Mo ppm ICP			
Ni ppm ICP			
Pb ppm ICP			
Sb ppm ICP			
Se ppm ICP			
Te ppm ICP			
Tl ppm ICP			
Zn ppm ICP			

6. Element associations

A Pearson product-moment correlation coefficient matrix of Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Ni, Pb, Sb, Se, Te, Tl, and Zn by modified aqua regia-ICP-MS and Au by INAA for the <0.063 mm fraction of 97 till samples reveals significant positive correlations ($>+0.65$) between As-Bi-Pb-Cd-Co, Zn-Cd-Mo-Pb-Se, and between Cu-Ni (Table 7). In the <0.063 mm B-C soil horizon samples (26) the most significant positive correlations ($>+0.65$) are between As-Cd-Hg, Cu-Ni-Tl and Zn-Cd-Mo (Table 8) and in 55 B-horizon soil samples, the significant positive correlations ($>+0.65$) are between As-Hg, Bi-Pb and Co-Ni-Tl (Table 9).

6.1. Elements in B-horizon soil and till size fractions

Box and whisker plots compare the range of values of Au, Ag, Cu, Pb, and Zn in till and the B-horizon soil samples sieved to 1-2 mm, 0.5-1 mm; 0.250-0.5 mm; 0.125-0.250 mm; 0.063-0.125 mm and <0.063 mm size fractions. Zinc (Fig. 6), Pb (Fig. 7), and Cu (Fig. 8) typically have higher median and outlier values in the <0.063 mm size fraction of the till samples compared with the metal content of larger size fractions. Zinc and Cu are also lower in all B-horizon soil sample fractions compared to values in the till fractions. Similar to Cu and Zn, Pb is higher in the <0.063 mm and 0.125 to 0.063 mm till sample fractions. However, the trend is reversed for the 1-2 mm, 0.5-1 mm; 0.250-0.5 mm; 0.125 mm fractions; in these, Pb is higher in the soil compared with the till. The similar Pb content of the larger grain sizes from the soil may reflect weathering of discrete Pb mineral grains from till or bedrock and their incorporation into the soil.

Most till size fractions contain more Au than the B-horizon soil size fractions (Fig. 9). However, one soil sample on the northern boundary of the survey area contains 464 ppb Au in the 1-2 mm fraction but the underlying till contains no detectable (i.e., >0.2 ppb) Au. Three till samples contain >48 ppb Au in all of the fractions, which could indicate that discrete Au grains are distributed through the till (i.e., the 'nugget effect'). The Ag content is higher in all soil fractions compared with the till (Fig. 10).

6.2. Variation of metals in B-horizon soil and till

The spatial variation of Au, As, Cu, Pb, Se and Zn in soil and till is shown in Figures 11 to 18. These elements are common geochemical pathfinders for Cu-Pb-Zn VMS (Moon et al., 2006; McClenaghan and Peter, 2016) and can be for quartz vein-hosted Au mineralization. Till samples were collected at two depths at a number of sites. For consistency, only element values for the deeper of the two samples are plotted as a bullet symbol in the figures. B-horizon soil values are plotted as a diamond symbol. Symbol size intervals correspond to the minimum to mean value, mean to 80th percentile value, 80th to 90th percentile value, 90th to 95th percentile value and 95th to the maximum value. Unless otherwise stated anomalous values are greater than the 95th percentile.

Several till samples on a road traverse along the northern

boundary of the survey area (A-A') have anomalous Pb concentrations ($>95^{\text{th}}$ percentile); at one site at the east end of this road, Pb concentration is 232 ppm (Fig. 11). Lead content is anomalous in both B-horizon soil and till at this site, but values decrease to less than 77 ppm to the west along a series of contiguous samples. In several of the till and B-horizon soil samples, grain size fractions >0.063 mm also contain anomalous Pb contents (Fig. 11). Isolated high Pb values are in the B-horizon soil and till on two other road traverses to the south and to the west (B-B'; C-C').

The locations of anomalous Zn concentrations in till are similar to those for Pb, with the highest values in samples along the northern boundary of the survey area (A-A', Figs. 12, 13). Zinc concentrations in till decrease to the west from a peak at the east end of the road traverse. However, the highest B-horizon soil Zn value is 500 m west of the highest Zn value in till. The variation of Se concentration, a VMS pathfinder element, (Fig. 14) reveals a single till sample with higher Se (>1.5 ppm) at the east end of the northern road traverse, corresponding to anomalous Pb and Zn values.

Several contiguous till samples along the northern road traverse have Cu concentrations between 95 and 111 ppm and an anomalous value (>111 ppm) at the east end of the traverse (Figs. 15, 16). Isolated Cu anomalies are also in the till and B-horizon soil along the southern road traverse and at the western end of the survey area, where high concentrations of Cu, Zn and Pb in till coincide with a northeast-trending fault.

High concentrations of Pb and Zn in soil and till samples are on the western boundary of the survey area (Figs. 11-13). Element values in the three samples from this profile at the site coincident with a northeast-trending fault (Fig. 12) are listed in Table 10. Most element contents are higher in the till than in the B horizon. Silver and Hg concentrations are exceptions to this trend and are higher in the B-horizon soil.

Four till samples have anomalous Au (INAA) values (>22 ppb) and three other sites contain >15 ppb in the soil (Fig. 17). One site west of where road traverses A-A' and B-B' meet has anomalous Au in soil and several contiguous till samples have anomalous As (Fig. 18). Three till samples contain anomalous Au concentrations in the sizes fractions >0.063 mm (Fig. 17). However, only one site on the southern road traverse has an anomalous Au content in the <0.063 mm size fractions (Table 11). One sample site on the northern road traverse contains 463 ppb Au in the 1 to 2 mm fraction of the B-horizon soil, but no Au in the <0.063 mm fraction of the soil and till.

7. Summary and discussion

This paper interprets data for 16 elements from till, B-C and B-horizon soil samples collected on the Ace property in central British Columbia. These elements are considered geochemical pathfinders for gold and base metal mineralization (e.g., Moon et al., 2006; McClenaghan and Peter, 2016; McClenaghan and Paulen, 2018), and significant positive correlations in the till samples could indicate precious metal (As-Sb), VMS

Table 7. Correlation coefficient matrix for Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Pb, Sb, Se, Te, Tl, and Zn analyzed by modified aqua regia-ICP-MS and Au by INAA in 97 till samples. Gold, Ag, and Hg are in ppb; other elements in ppm. The data are log transformed. Coefficients greater than +0.65 are highlighted in red.

	Ag	As	Au	Au INA	Bi	Cd	Co	Cu	Hg	Mo	Ni	Pb	Sb	Se	Te	Tl	Zn
Ag	1.00																
As	0.47	1.00															
Au	0.19	0.28	1.00														
Au INA	0.10	-0.08	0.21	1.00													
Bi	0.44	0.45	0.36	0.24	1.00												
Cd	0.37	0.49	0.25	0.20	0.51	1.00											
Co	0.31	0.43	0.28	0.23	0.67	0.51	1.00										
Cu	0.11	0.30	0.35	0.25	0.51	0.45	0.77	1.00									
Hg	0.26	0.23	0.24	0.01	0.26	0.29	0.27	0.07	1.00								
Mo	0.32	0.41	0.22	0.15	0.58	0.75	0.52	0.43	0.39	1.00							
Ni	0.29	0.38	0.23	0.18	0.56	0.44	0.81	0.70	0.18	0.42	1.00						
Pb	0.46	0.68	0.38	0.16	0.72	0.69	0.78	0.57	0.36	0.69	0.63	1.00					
Sb	0.28	0.55	0.30	0.15	0.26	0.63	0.29	0.40	0.17	0.44	0.22	0.50	1.00				
Se	0.23	0.36	0.19	0.13	0.42	0.60	0.45	0.28	0.39	0.68	0.46	0.53	0.38	1.00			
Te	0.42	0.41	0.32	0.18	0.71	0.51	0.67	0.61	0.23	0.57	0.55	0.66	0.27	0.38	1.00		
Tl	-0.16	-0.14	-0.21	-0.07	0.09	0.10	0.30	0.33	0.09	0.22	0.19	0.13	-0.02	-0.07	0.16	1.00	
Zn	0.32	0.46	0.22	0.21	0.53	0.79	0.61	0.51	0.19	0.76	0.57	0.78	0.49	0.53	0.51	0.09	1.00

Table 8. Correlation coefficient matrix for Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Pb, Sb, Se, Te, Tl, and Zn analyzed by modified aqua regia-ICP-MS and Au by INAA in 26 B-C horizon soil samples. Gold, Ag and Hg are in ppb; other elements in ppm. The data are log transformed. Coefficients greater than +0.65 are highlighted in red.

	Ag	As	Au	Au INAA	Bi	Cd	Co	Cu	Hg	Mo	Ni	Pb	Sb	Se	Te	Tl	Zn
Ag	1.00																
As	0.23	1.00															
Au	-0.09	0.31	1.00														
Au INAA	0.15	0.12	0.23	1.00													
Bi	0.16	0.30	0.29	0.16	1.00												
Cd	0.82	0.22	0.03	0.11	0.13	1.00											
Co	0.05	0.56	0.40	0.19	0.34	0.17	1.00										
Cu	-0.12	0.30	0.46	0.19	0.36	-0.06	0.81	1.00									
Hg	0.67	0.06	-0.08	0.03	0.21	0.67	-0.03	-0.20	1.00								
Mo	0.51	-0.19	-0.04	0.18	0.20	0.58	-0.12	-0.23	0.42	1.00							
Ni	0.09	0.56	0.44	0.12	0.45	0.28	0.87	0.73	0.08	0.12	1.00						
Pb	0.23	0.49	0.47	0.20	0.59	0.45	0.64	0.53	0.12	0.15	0.72	1.00					
Sb	-0.12	0.25	0.04	0.41	0.26	0.05	0.10	0.11	0.11	-0.04	0.13	0.12	1.00				
Se	0.40	0.09	0.00	0.01	0.27	0.49	0.07	-0.13	0.45	0.40	0.12	0.46	0.02	1.00			
Te	0.25	0.35	-0.04	0.11	0.63	0.22	0.20	0.03	0.39	0.30	0.34	0.42	0.29	0.46	1.00		
Tl	-0.09	0.17	0.29	-0.09	0.20	0.23	0.66	0.65	-0.08	0.01	0.75	0.66	-0.01	-0.06	0.12	1.00	
Zn	0.54	0.03	-0.01	0.14	0.09	0.70	0.24	-0.02	0.42	0.71	0.37	0.35	-0.02	0.40	0.31	0.28	1.00

Table 9. Correlation coefficient matrix for Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Pb, Sb, Se, Te, Tl, and Zn analyzed by modified aqua regia-ICP-MS and Au by INAA in 55 B-horizon soil samples. Gold, Ag and Hg are in ppb; other elements in ppm. The data are log transformed. Coefficients greater than +0.65 are highlighted in red.

	Ag	As	Au	Au INAA	Bi	Cd	Co	Cu	Hg	Mo	Ni	Pb	Sb	Se	Te	Tl	Zn
Ag	1.00																
As	0.14	1.00															
Au	-0.08	0.29	1.00														
Au INAA	0.14	0.29	0.36	1.00													
Bi	0.07	0.31	0.30	0.46	1.00												
Cd	0.57	0.29	-0.16	0.16	0.13	1.00											
Co	-0.06	0.21	0.17	0.06	0.01	0.12	1.00										
Cu	-0.07	-0.03	0.20	-0.04	-0.16	-0.08	0.70	1.00									
Hg	0.69	0.12	-0.12	0.06	-0.17	0.31	-0.12	-0.12	1.00								
Mo	0.47	0.29	-0.18	0.31	0.42	0.57	-0.24	-0.38	0.18	1.00							
Ni	-0.26	0.05	0.17	0.02	0.08	-0.07	0.76	0.51	-0.36	-0.30	1.00						
Pb	0.18	0.49	0.09	0.48	0.67	0.40	0.16	-0.08	0.02	0.44	0.18	1.00					
Sb	0.42	0.35	-0.01	0.25	0.20	0.55	0.16	0.04	0.37	0.37	-0.03	0.42	1.00				
Se	0.34	0.40	0.13	0.27	0.08	0.47	0.04	-0.10	0.36	0.33	-0.16	0.30	0.43	1.00			
Te	0.03	0.19	0.12	0.21	0.61	0.04	-0.05	-0.18	-0.14	0.39	0.08	0.38	0.10	0.03	1.00		
Tl	-0.34	-0.03	0.19	-0.03	-0.05	-0.12	0.71	0.58	-0.45	-0.36	0.77	0.09	-0.08	-0.22	-0.08	1.00	
Zn	0.36	0.29	0.03	0.21	0.37	0.55	0.28	-0.08	0.02	0.48	0.36	0.52	0.35	0.21	0.34	0.16	1.00

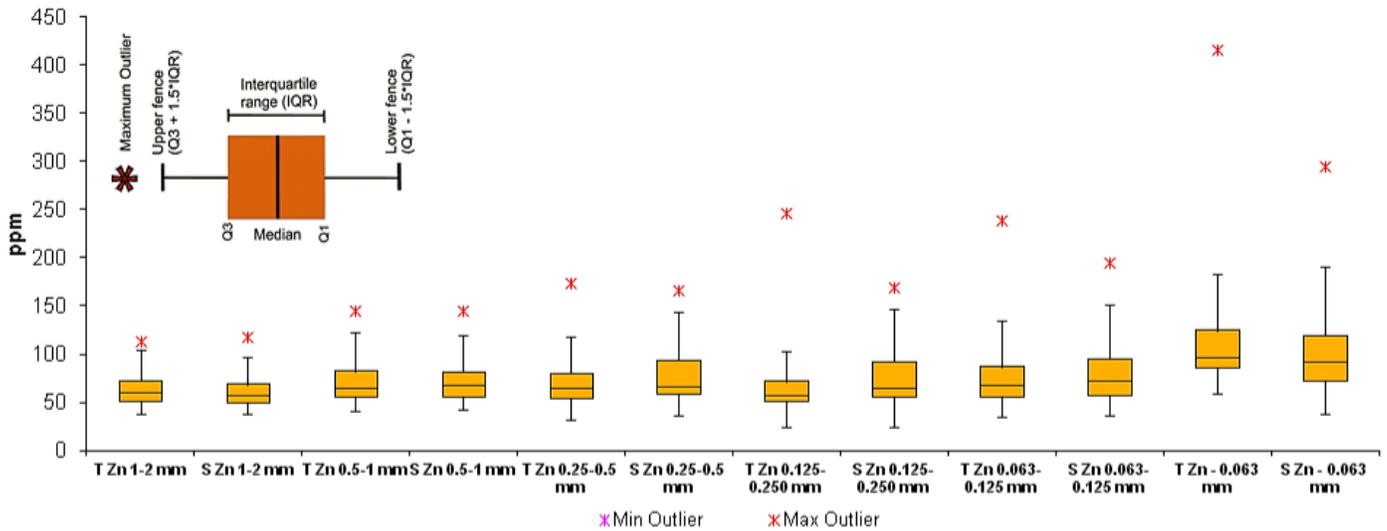


Fig. 6. Box and whisker plot for Zn by aqua regia-ICP-MS in till (T) and B-horizon soil (S) in size fractions ranging from 1-2 mm to <0.063 mm.

(Zn-Cd-Pb-Se), and magmatic massive sulphide (Cu-Co-Ni) mineralization. These element associations are also present, but modified, in the B-C and B-horizon soil samples. In the B-horizon soil, there is a significant correlation between Au and As that is common in Au mineralization. Selected elements in different size fractions show that Au, Cu, Pb, and Zn concentrations are generally higher in the <0.063 mm fraction of till (e.g., McClenaghan and DiLabio, 1993), whereas Ag and Hg concentrations are elevated in the B-horizon soil. The higher metal content of the <0.063 mm fraction relative to the coarser

fractions of till in this study, is commonly observed elsewhere (e.g., DiLabio, 1988, 1995). The higher metal concentrations in the finer fraction usually reflects the finer grain size of the metals in the host rocks as well as diminution of ore minerals during glacial erosion, transport, and deposition to silt and clay sized particles (e.g., McClenaghan and Peter, 2016). In experimental studies that examined the origin of the fine fraction in tills, Mäkinen (1995) observed that as the degree of sediment grinding increased, the contents of some metals (Co, Cu, Fe, Mn, Ni, Zn) decreased in comparison to the overall

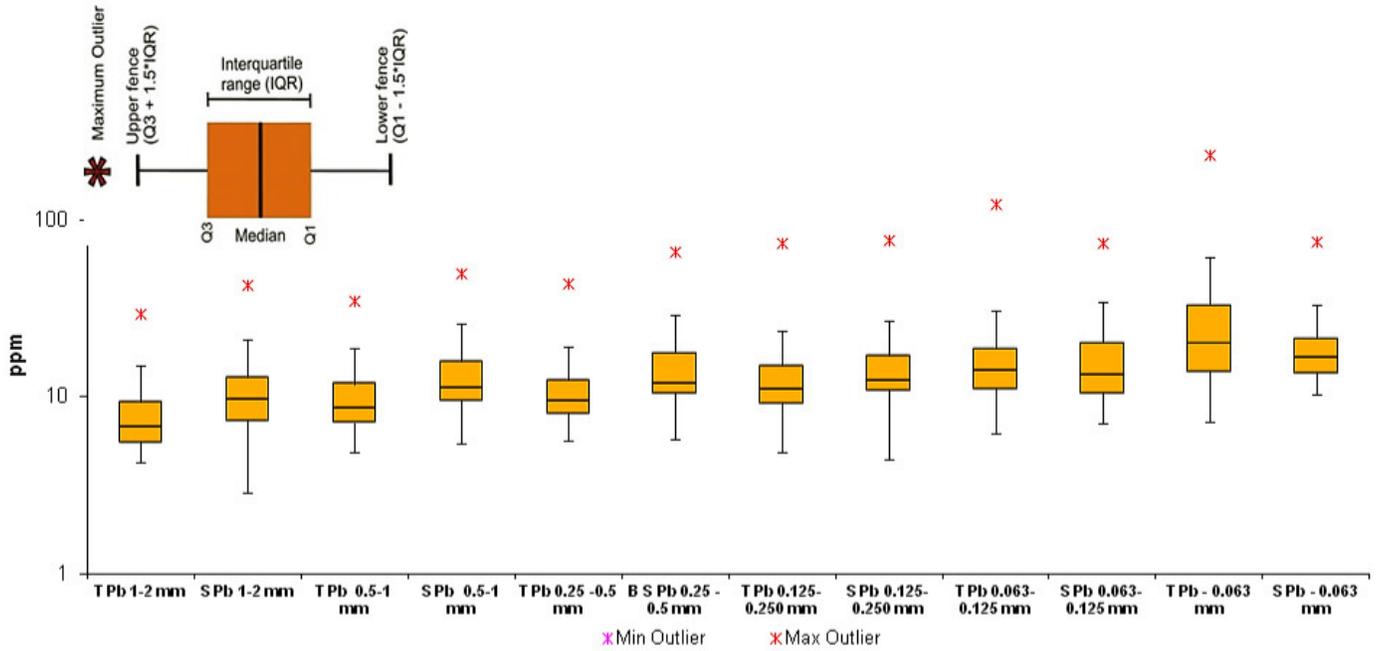


Fig. 7. Box and whisker plot for Pb by aqua regia-ICP-MS in till (T) and B-horizon soil (S) in size fractions ranging from 1-2 mm to <0.063 mm (see Figure 6 for box plot legend).

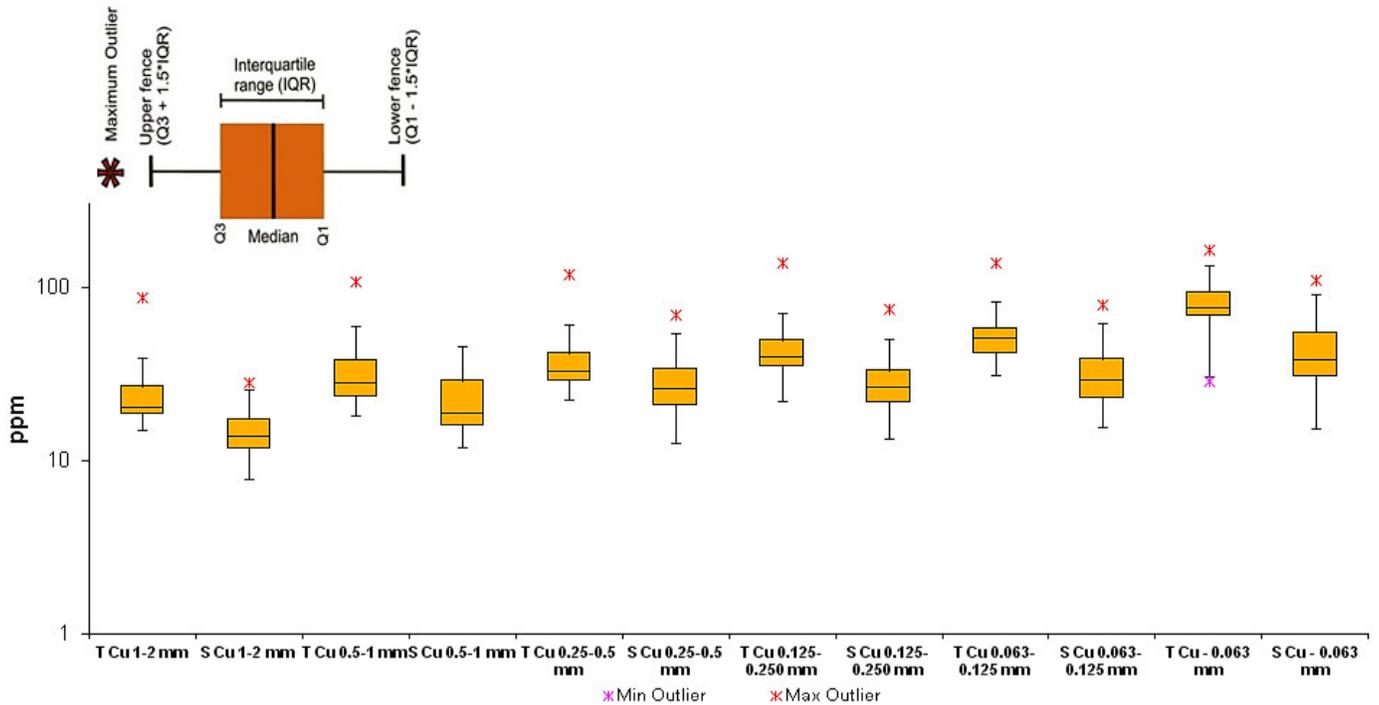


Fig. 8. Box and whisker plot for Cu by aqua regia-ICP-MS in till (T) and B-horizon soil (S) in size fractions ranging from 1-2 mm to <0.063 mm (see Figure 6 for box plot legend).

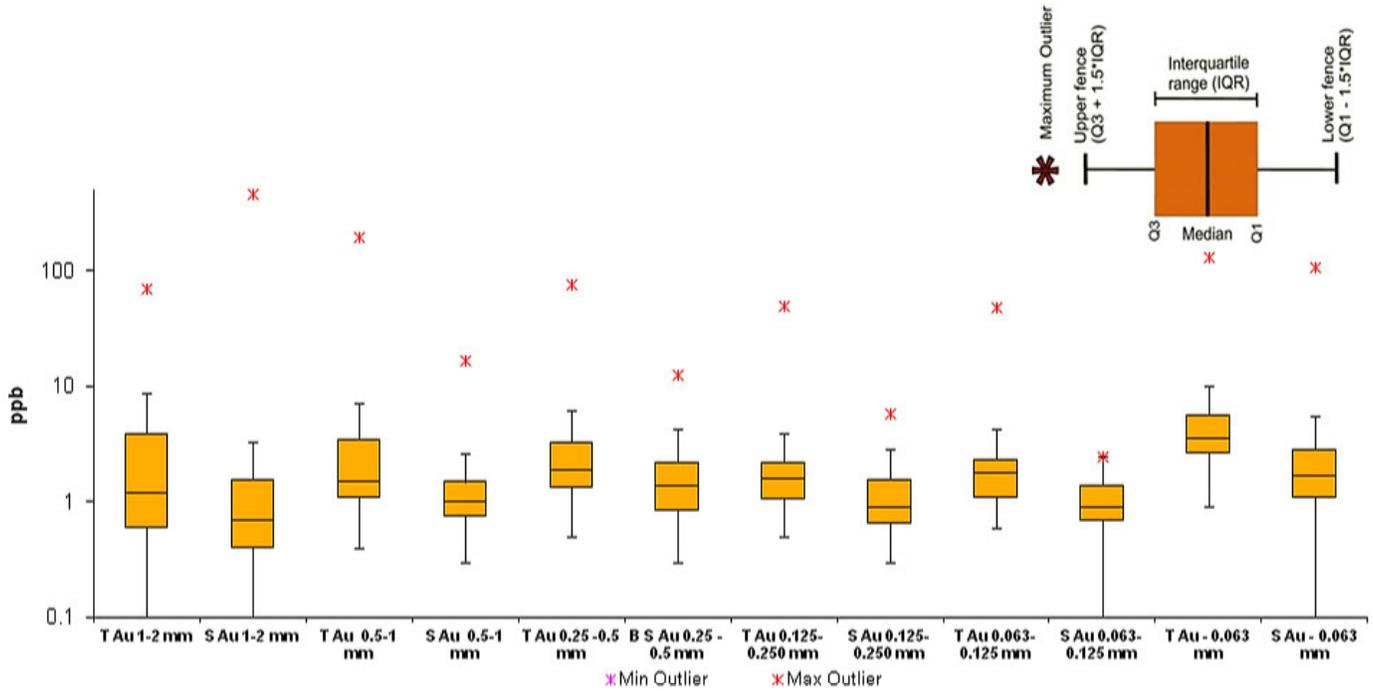


Fig. 9. Box and whisker plot for Au by aqua regia-ICP-MS in till (T) and B-horizon soil (S) in size fractions ranging from 1-2 mm to <0.063 mm (see Figure 6 for box plot legend).

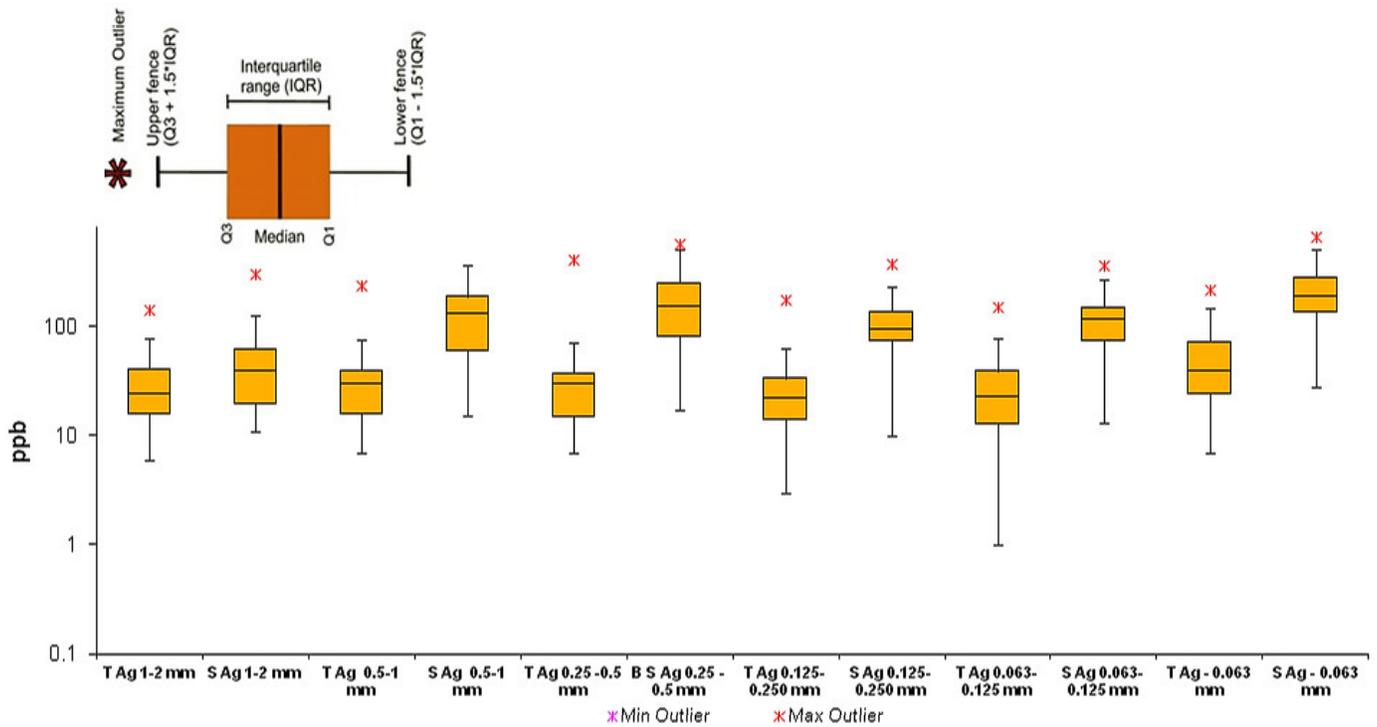


Fig. 10. Box and whisker plot for Ag by aqua regia-ICP-MS in till (T) and B-horizon soil (S) in size fractions ranging from 1-2 mm to 0.063 mm (see Figure 6 for box plot legend).

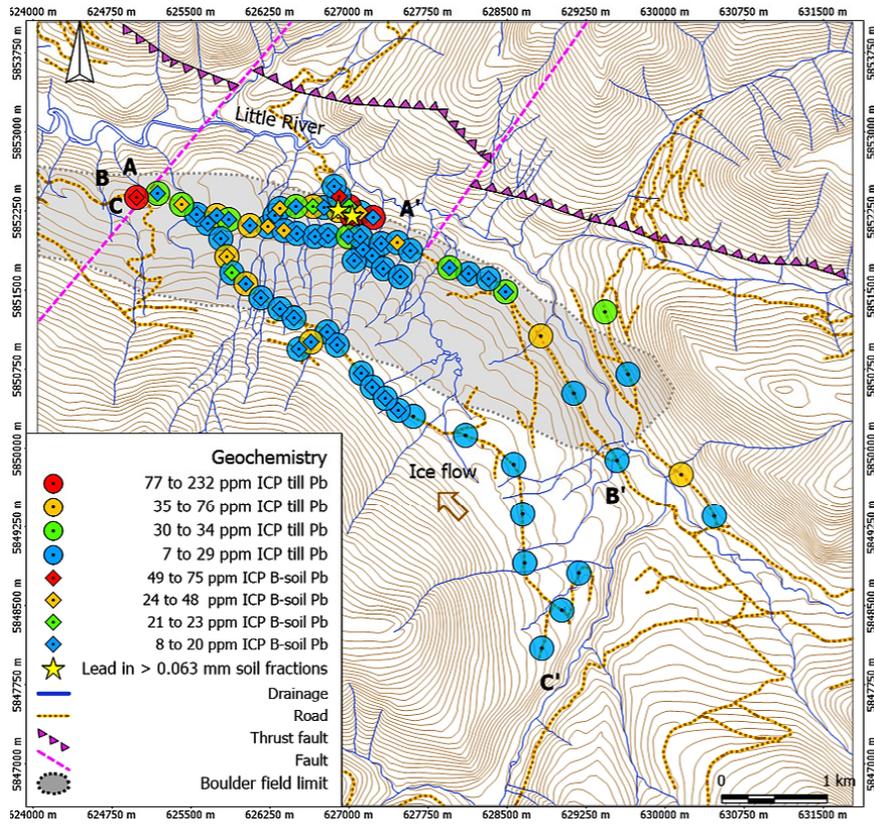


Fig. 11. Lead concentration in the <0.063 mm fraction of till and B-horizon soil determined by aqua regia-ICP-MS. A-A'; B-B' and C-C' refer to road traverses described in the text.

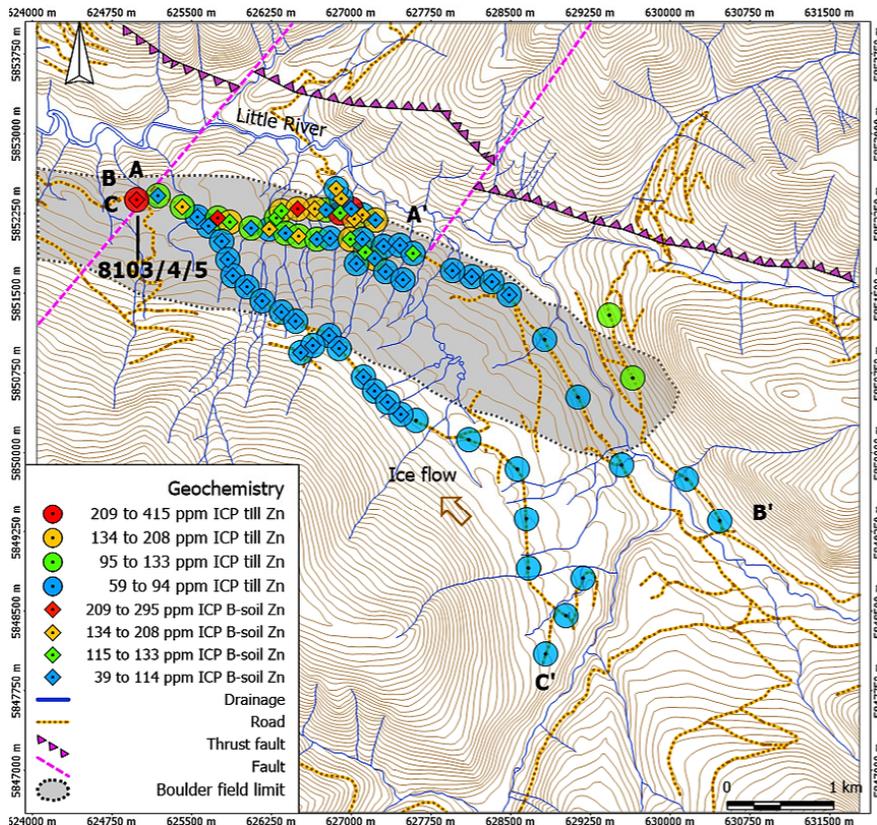


Fig. 12. Zinc concentration in the <0.063 mm fraction of till and B-horizon soil by aqua regia-ICP-MS.

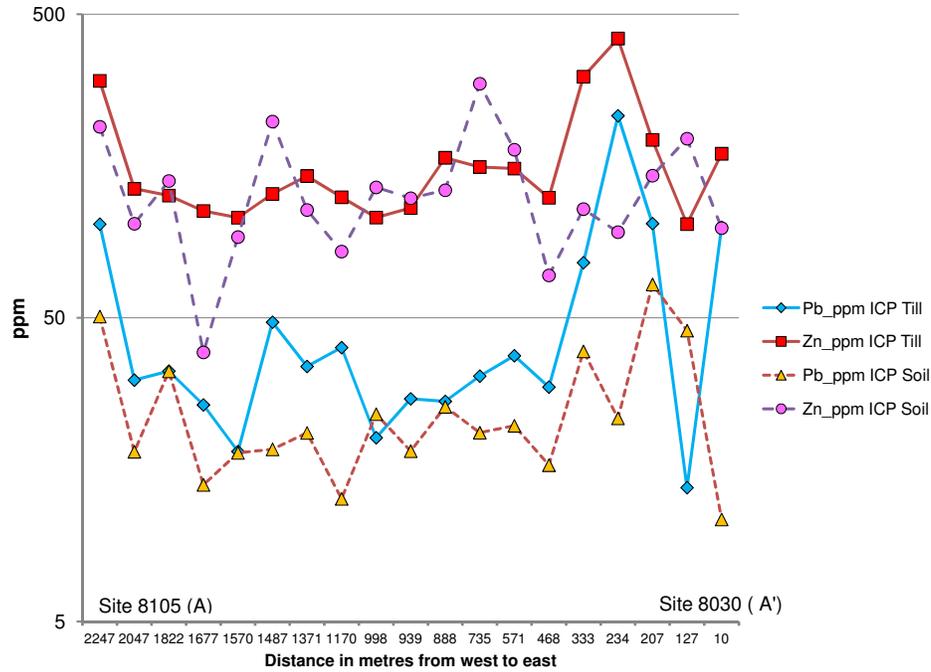


Fig. 13. Lead and Zn concentration in the <0.063 mm fraction of till and B-horizon soil determined by aqua regia-ICP-MS along the northern W-E road traverse (A-A').

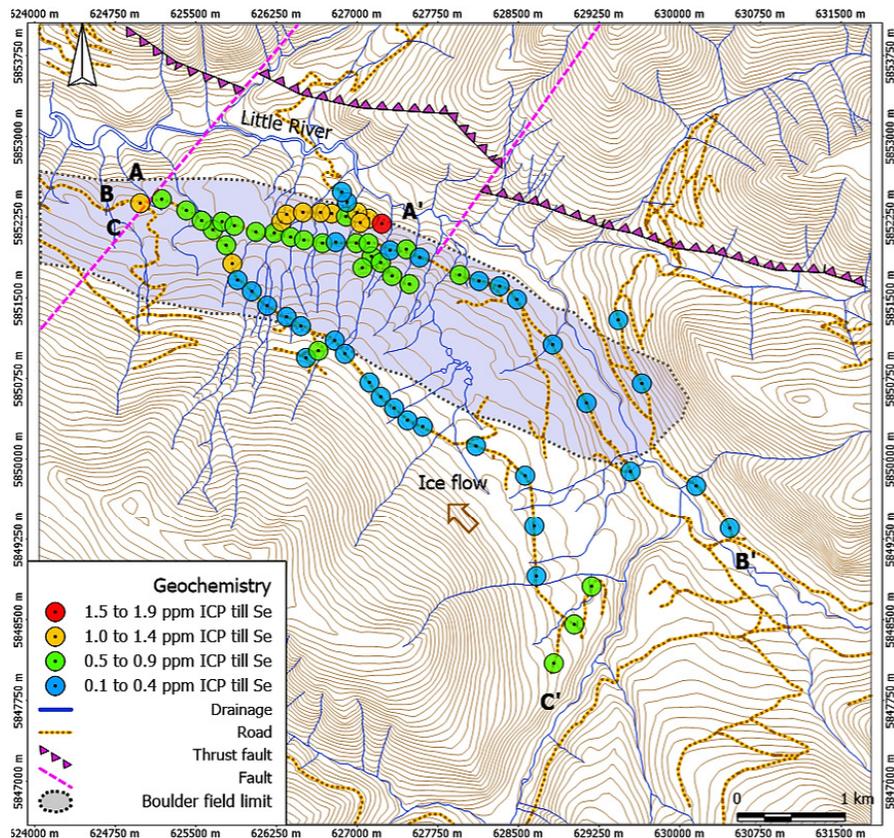


Fig. 14. Selenium concentration in the <0.063 mm fraction of till analyzed by aqua regia-ICP-MS.

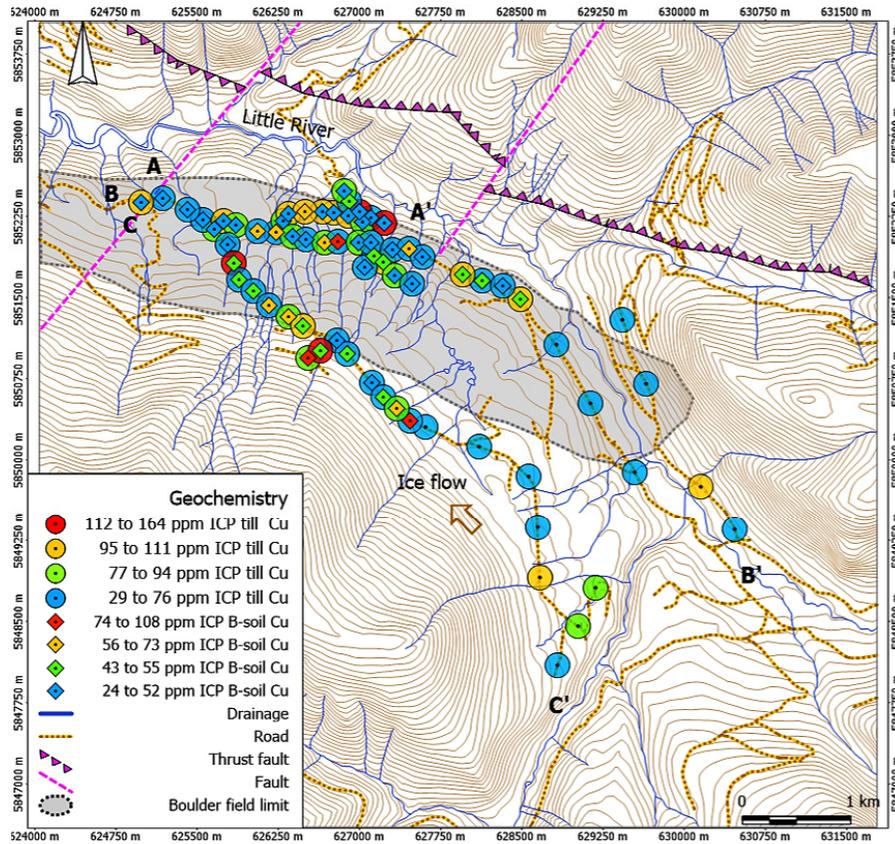


Fig. 15. Copper concentration in the <0.063 mm fraction of till and B-horizon soil analyzed by aqua regia-ICP-MS.

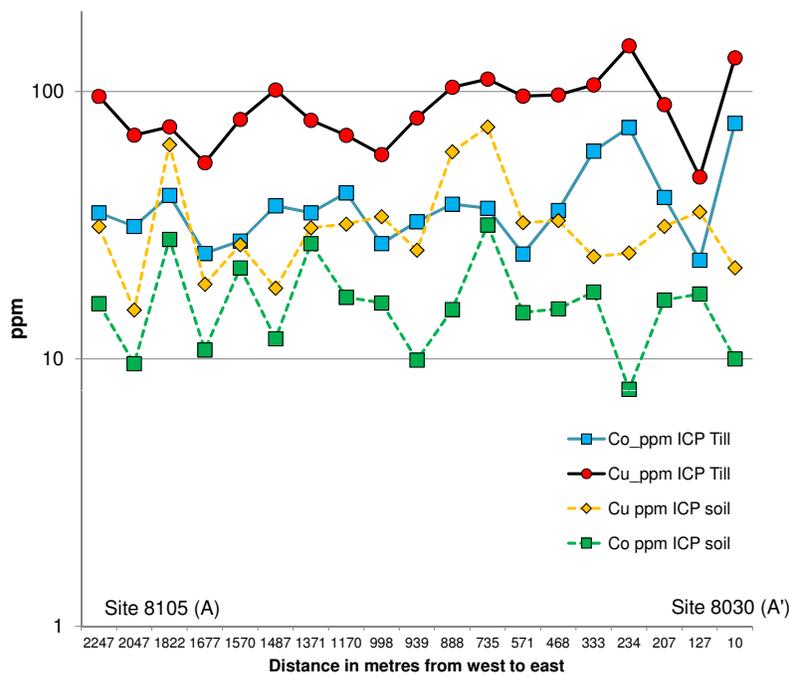


Fig. 16. Comparison of Cu and Co concentrations in the <0.063 mm fraction of till and B-horizon soil samples determined by aqua regia-ICP-MS along the northern road traverse A-A'.

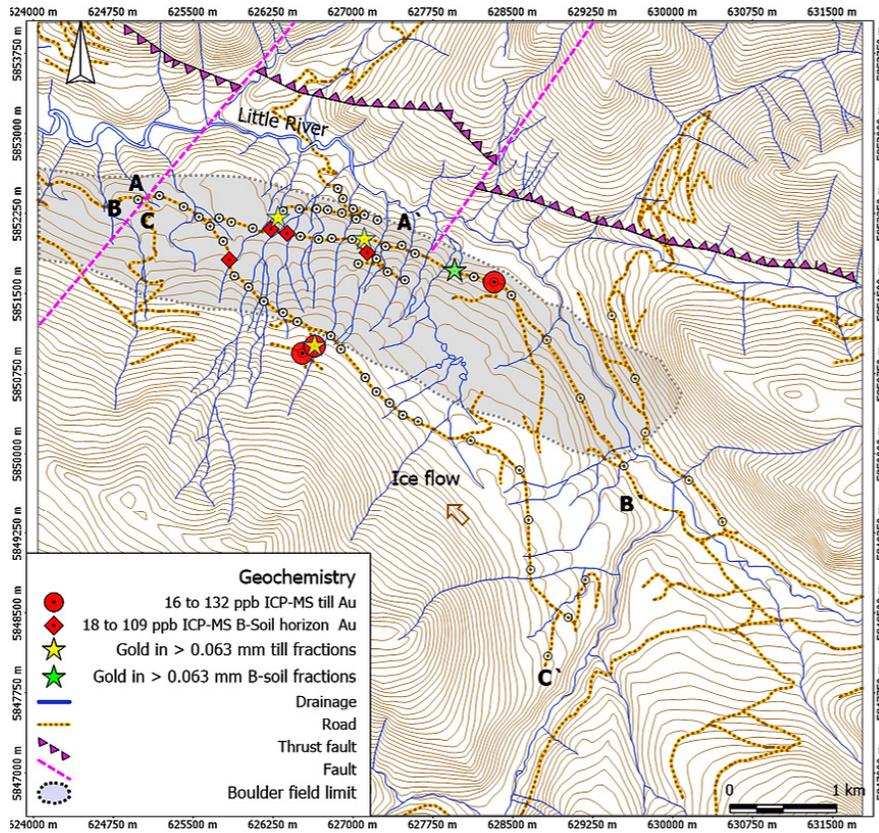


Fig. 17. Anomalous Au concentrations in B-horizon soil and till in the <0.063 mm fraction determined by modified aqua regia-ICP-MS. Sites with anomalous Au in the >0.063 mm fractions are highlighted on the map as yellow or green star symbols.

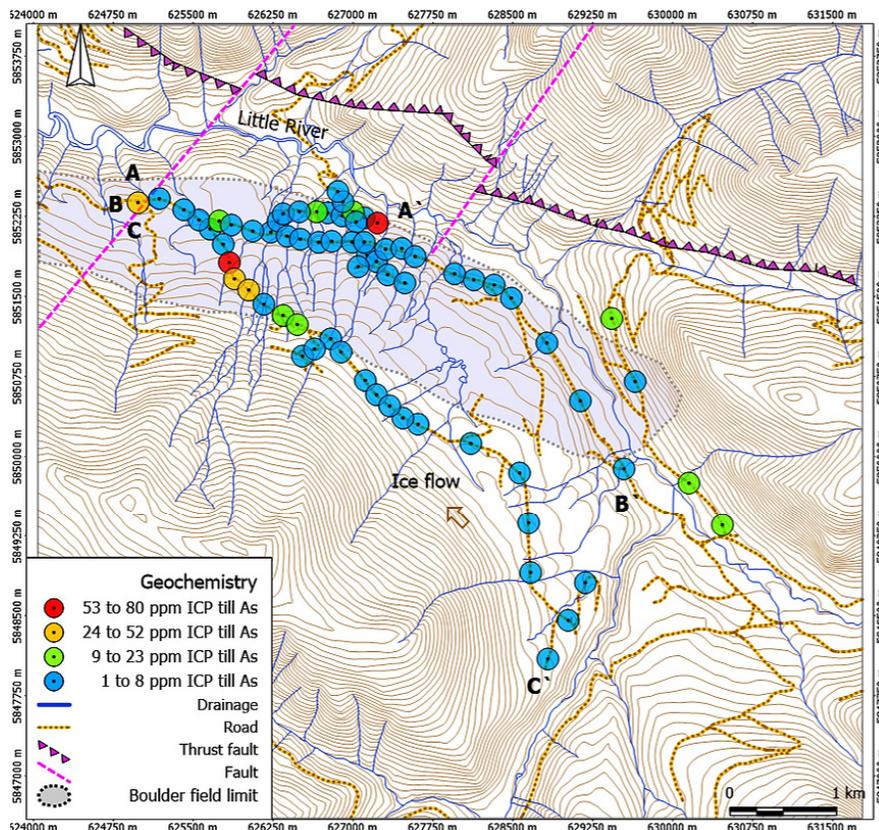


Fig. 18. Arsenic concentrations in the <0.063 mm fraction of till determined by modified aqua regia-ICP-MS.

Table 10. Element concentrations in B-horizon soil and till samples 8103, 8104 and 8185 at the site on the west end of the sampling transect coincident with a northeast-trending fault (see Figure 12). Silver, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Sb, Se, Pb, Te, and Zn analyzed by modified aqua regia-ICP-MS and Au by INAA in the <0.063 mm fraction.

Sample Number	8103	8104	8105
Sample Depth (m)	0.1	1.2	1.85
Horizon	B-soil	Till	Till
Ag ppb ICPMS	665	82	37
As ppm ICPMS	22.3	53.3	50.3
Au ppb ICPMS	2.1	12.6	15.9
Au ppb INAA	15	1	11
Bi ppm ICPMS	1.72	2.02	2.67
Cd ppm ICPMS	0.67	0.69	0.84
Co ppm ICPMS	16.2	26.5	35.2
Cu ppm ICPMS	34.07	80.41	95.95
Hg ppb ICPMS	75	30	26
Mo ppm ICPMS	8.88	12.87	16.69
Pb ppm ICPMS	50.53	63.42	101.77
Sb ppm ICPMS	0.15	0.2	0.33
Se ppm ICPMS	1.1	1.2	1.2
Te ppm ICPMS	0.04	0.08	0.13
Zn ppm ICPMS	213	204.7	301.8

Table 11. Gold outlier values by modified aqua regia-ICP-MS in various size fractions of till and B-horizon soil samples shown in the box and whisker plots.

Fraction	Au Till Site	Au ppb	Au soil site	Au ppb
1.0 - 2.0 mm	8011	71	8075	463
< 0.063 mm	8011	12.2	8075	1.2
0.5 - 1.0 mm	8068	198	-	-
< 0.063 mm	8068	10.1	-	-
0.25 - 0.5 mm	8215	77	-	-
0.125 - 0.25 mm	8215	50	-	-
0.063 - 0.125 mm	8215	48	-	-
< 0.063 mm	8215	52.2	-	-

composition of the coarser fraction. Others have shown that base metals, gold, and platinum group element contents tend to be higher in the fine (<0.063 mm) till fraction (Nevalainen, 1989; Salminen et al., 1989; Shilts, 1993). Weathering of the till will release these elements into the soil where the geochemical processes active in the B-horizon soil are responsible for the ultimate trace metal anomaly size, shape, and contrast (DiLabio, 1995).

In the B-horizon soil, geochemically mobile elements (e.g., As, Cu, Co, and Zn) accumulate from meteoric water percolating downward through the soil by absorption onto clay minerals and secondary Fe and Mn oxides (McLean and Bledsoe, 1992). Depending on soil chemistry and especially pH, metals such as Cu, Zn, Ag, and Hg can preferentially complex with soil organic matter (McLean and Bledsoe, 1992). Complexing can explain the higher Ag concentrations in the 0.25 to 0.5 mm fraction

of the B-horizon soil samples through metal bonding to soil humus, a phenomenon noted by Cook and Dunn (2007). Native Au and Pb minerals are more resistant to surface chemical weathering and can exist as particles larger than 0.063 mm in till and soil. Some of the till and B-horizon soil samples in the present study have high Au and Pb concentrations in several size fractions, likely indicating the presence of the native Au and Pb-rich mineral grains.

Till samples containing >35 ppm Pb and >134 ppm Zn, along with anomalous Cu and Co, form a linear pattern aligned east-west on the northern edge of the survey area (Fig. 19). Peak metal concentrations are at the east end of this anomaly and they decrease to the west, suggesting a dispersal train of sulphide debris (Fig. 20). Conceivably, the Little River topography could have diverted the regional southeast to northwest advancing ice into the valley, resulting in east to west deposition of till.

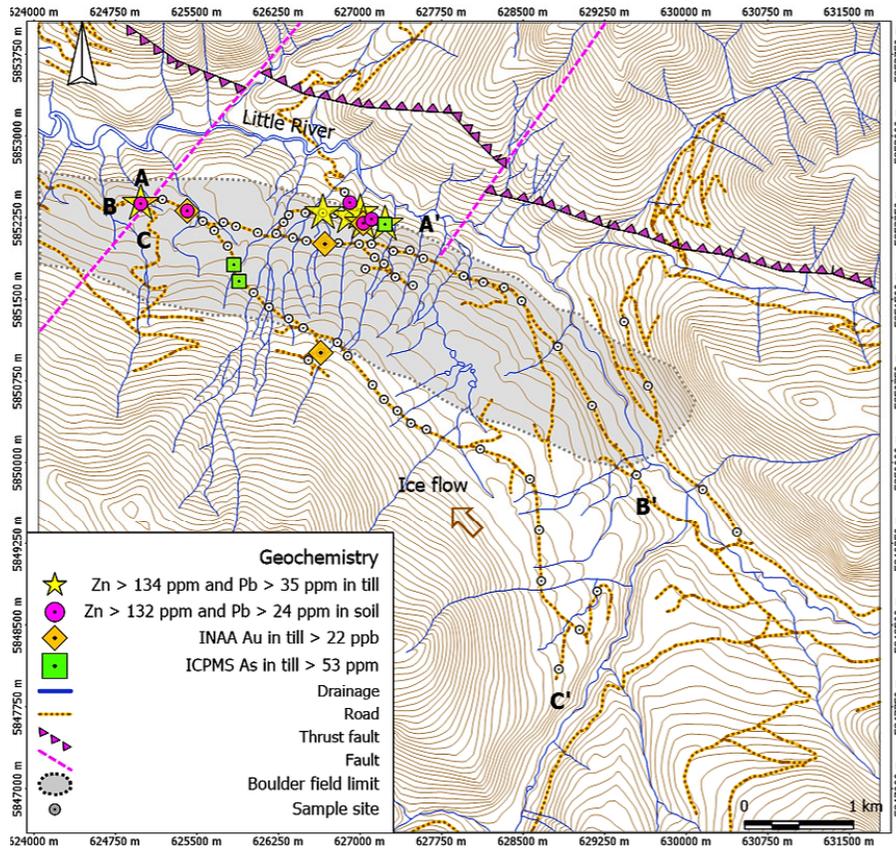


Fig.19. Lead and Zn values >80 percentile in the <0.063 mm fraction of till and B-horizon soil samples analyzed by aqua regia-ICP-MS. The location of anomalous Au (INAA) and As (modified aqua regia-ICP-MS) concentrations in till are indicated by yellow and green symbols.

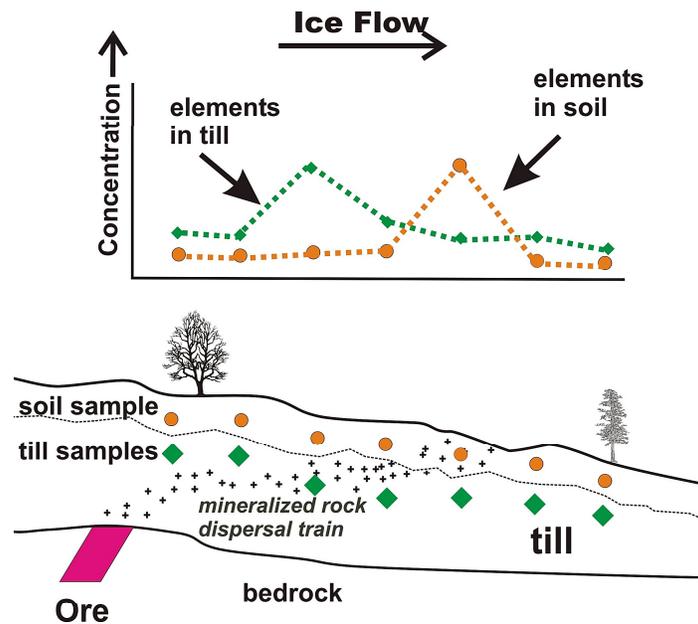


Fig. 20. Idealized geochemical profiles from the analysis of B-horizon soil and till samples intersecting a mineralized bedrock down-ice dispersal plume (after Drake, 1983; Miller, 1984; Hicken and Plouffe, 2017; McClenaghan and Paulen, 2018).

Separation of the Pb, Zn, Cu, and Co B-soil anomaly 500 metres to the west and down ice from the Pb-Zn-Cu-Co till anomaly is consistent with a till dispersal model described by Miller (1984) and subsequently refined by Hickin et al. (2017) and McClenaghan and Paulen (2018). However, the till at surface in this area is colluviated and the Pb-Zn B-soil anomaly trends to the north towards the Little River. Colluviation and reworking of the till may explain anomalous Pb and Au values in larger grain size fractions of the B-horizon soil and till due to the presence of discrete mineral grains.

Anomalous Ag, Au, As, Co, Cu, Pb, and Zn values with elevated Se values in the B-horizon soil and till from a site near a northeast-trending fault on the western boundary of the survey area (Fig. 11) may indicate that the structure is mineralized and is the source of the metals in the till. A geochemical profile at this site (Table 10) shows the contrast between elements such as As, Au, Bi, Cu, Co, Pb, and Zn. These are elevated in the till whereas Ag and Hg are higher in the B-horizon soil. The profile illustrates that an element signature in soil can differ from that in till and the difference should be considered when interpreting results of a geochemical survey.

Although As is a common pathfinder for Au, some till samples with anomalous Au values lack elevated As concentrations. However, individual sites along the Co-Cu-Pb-Zn till anomaly on the northern road traverse (A-A') do contain anomalous Au and As. The presence of the anomalous Au and As in this dispersal train could reflect a precious metal enrichment of the massive sulphides or a separate Au mineralized quartz vein. Several till and B-horizon soil samples with anomalous Au in the larger grain size fraction suggest the presence of large (>0.063 mm) Au grains that could have been derived from a more proximal bedrock source rather than having been entrained and transported farther down ice. Till samples with anomalous As or Au contents appear to be aligned along a northeast trend across the survey area and this could reflect the existence of mineralized Au-quartz veins related to the faults. Future work could include bulk till sampling for gold grain recovery to examine the gold grain size distribution and morphology to establish transport distance and possible bedrock source (see e.g., DiLabio, 1990; McClenaghan and Cabri, 2011).

The combination till and soil survey did not provide insights into the location of the bedrock source of the mineralized boulder train. Given that glacial transport was from the southeast, the boulders were likely transported from an unknown distance up-ice of the survey area. Additional till sampling up ice (southeast) of the current survey area would help identify the boulder train's bedrock source.

8. Conclusions

Till, B-C transitional horizon and B-horizon soil samples from 85 sites have been collected on the Ace property in central British Columbia and analyzed for more than 50 minor and trace elements. Based on data for 16 elements commonly considered geochemical pathfinders for Au and base metals the following conclusions are made.

- Gold, As, Co, Cu, Pb, Se, and Zn concentrations are higher in the <0.063 mm fraction of till compared to levels in the <0.063 mm of the B-horizon soil, reflecting both the nature of the mineralization in the bedrock source and the effects of comminution during glacial transport and deposition. Silver and Hg concentrations are higher in the B-horizon soil, which may reflect their preferential complexing/binding with organic matter. Data from different grain size fractions indicate that Au and Pb may also be present as larger (>0.063 mm) mineral grains in B-horizon soil and till in addition to grains that are <0.063 mm.
- Anomalous Au, Co, Cu, Pb, Se, and Zn concentrations in till and B-horizon soil outline a narrow ribbon-shaped dispersal train along the northern border of the area that was formed initially in till deposited from by ice flowing east to west and subsequently modified by gravity processes (northward displacement) on the steep hill slope to form colluvium. Trace element profiles along the anomaly axis show separation of the B-horizon soil anomaly 500 m to the west of the till anomaly. This pattern is consistent with a model of Pb-Zn-Cu sulphide transport in till from a mineralized bedrock source at the east end of the dispersal train.
- A potentially mineralized northeast-trending fault at the west end of the survey area may be the source for a Au, Cu, Co, Pb, Zn anomaly in both soil and till. The distribution of till and B-horizon soil Au-As anomalies across the survey area could also reflect the presence of northeast-trending Au-rich quartz veins.

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