

# Post-mining hydrogeochemical conditions, Brewery Creek gold deposit, central Yukon

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## ABSTRACT

A reconnaissance-level study of post-mining hydrogeochemical conditions was carried out at the Brewery Creek gold deposit within the Tintina Gold Province. The deposit is characterized by epizonal mineralization with a consistent arsenic-gold-mercury-antimony geochemical signature. Surface discharges and seeps in the area are naturally alkaline (pH=7.6-8.2), Ca-HCO<sub>3</sub><sup>-</sup>-SO<sub>4</sub><sup>2-</sup> waters. Upstream from the recognized mineralization, waters contain <3 µg/L As and <1 µg/L Sb. Water samples immediately downstream from the ore bodies show maximum concentrations of 18 µg/L dissolved and 47 µg/L total arsenic, and 18 µg/L dissolved and 21 µg/L total antimony. Two kilometres below the mineralization, on lower Laura Creek, arsenic concentrations are diluted to background levels of <3 µg/L, and antimony levels are still slightly elevated at 9-10 µg/L. Comparison with hydrogeochemical data from Donlin Creek, an undeveloped epizonal deposit in Alaska, indicates that elevated concentrations of a few tens of µg/L arsenic and antimony are typical of waters draining such gold systems, regardless of their state of development. In addition to their usefulness for the construction of geoenvironmental models, these data also provide information for establishing exploration programs utilizing water sampling.

## RÉSUMÉ

Une étude de reconnaissance des conditions hydrogéochimiques postérieures à l'exploitation minière a été réalisée au gîte aurifère de Brewery Creek dans la province aurifère de Tintina. Le gîte est caractérisé par une minéralisation épizonale affichant une signature géochimique cohérente d'arsenic-or-mercure-antimoine. Les rejets de surface et les infiltrations dans la zone sont des eaux de Ca-HCO<sub>3</sub><sup>-</sup>-SO<sub>4</sub><sup>2-</sup> naturellement alcalines (pH=7,6-8,2). En amont de la minéralisation connue, les eaux contiennent <3 µg/L de As et <1 µg/L de Sb. Les échantillons d'eau prélevés tout juste en aval des massifs minéralisés ont des concentrations maximales de 18 µg/L de As dissous et de 47 µg/L de As total, ainsi que 18 de Sb dissous et 21 de Sb total. À deux kilomètres au-dessous de la minéralisation, sur le ruisseau Laura inférieur, les concentrations d'arsenic sont diluées à des niveaux de fond de <3 µg/L et celles d'antimoine sont légèrement plus élevées à 9-10 µg/L. En comparant ces données avec les données hydrogéochimiques de Donlin Creek, un gisement épizonal non exploité en Alaska, il ressort que les concentrations élevées de quelques dizaines de µg/L d'arsenic et d'antimoine sont représentatives des eaux qui drainent des systèmes aurifères quel que soit leur état de mise en valeur. Ces données servent non seulement à la construction de modèles géoenvironnementaux, mais aussi à la conception de programmes d'exploration à partir d'échantillons d'eau.

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## INTRODUCTION

The Tintina Gold Province (TGP) extends from southwestern Alaska to eastern Yukon and comprises numerous individual gold belts and districts. The province is characterized by gold lodes showing a spatial association with mid-Cretaceous plutons in its east and central parts, and with latest Cretaceous plutons in the west. Mineralization styles differ greatly throughout the TGP. Most deposits, surrounding a central, causative pluton, typically occur as auriferous sheeted quartz-feldspar veins where mineralized rock is localized in the apical parts of the plutons or in immediately adjacent hornfels (Hart et al., 2002). These veins are characterized by a gold-bismuth-tellurium-tungsten geochemical signature and low sulphide mineral content (< 0.5% volume), such as those found at the Fort Knox deposit and the Dublin Gulch prospect (Hart et al., 2000; Goldfarb et al., 2000). A less understood deposit style, also associated with the Cretaceous plutons, is epizonal fracture networks within carbonaceous sedimentary rocks and/or felsic dykes and sills. These deposits have a lower temperature arsenic-gold-mercury-antimony signature and a high sulphide mineral content (>2% volume). The most notable of these are True North and Donlin Creek in Alaska, and Brewery Creek in the Yukon (Hart et al., 2002).

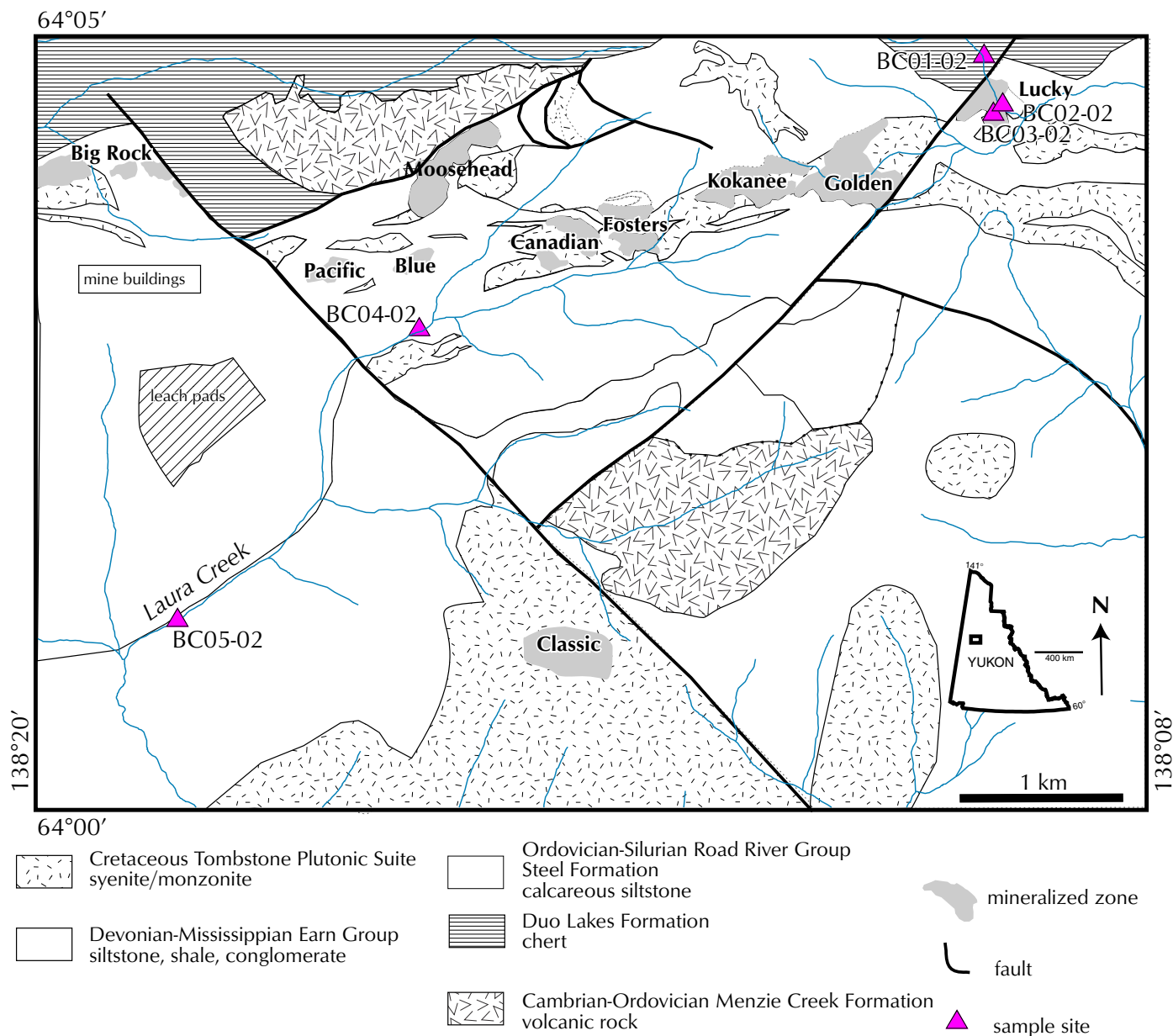
As part of an ongoing study to characterize the environmental geochemistry of epizonal deposits throughout the TGP, the U.S. Geological Survey, in collaboration with the Yukon Geological Survey, is examining the pre-, syn- and post-mining, geochemistry of ground and surface water at the Donlin Creek, True North and Brewery Creek (Yukon MINFILE 2002, 116B 160, Deklerk, 2002) deposits, respectively. During the 2002 field season, a reconnaissance-level sampling program was undertaken at Brewery Creek. One aim of this work is to create a comprehensive geoenvironmental model that will help decision makers better understand the mobility of potentially toxic metals, such as arsenic, antimony and mercury within the environment surrounding this style of gold mineralization. In addition, these trace element data, as well as stable isotope information, can be evaluated as potential pathfinders for future exploration work across the TGP. In this paper, we present the results from this investigation and interpret these in the context of the deposit, and also provide comparisons with water geochemistry at the undeveloped Donlin Creek deposit and presently producing True North deposit.

## GEOLOGIC SETTING AND MINERALIZATION

The Brewery Creek property is located approximately 60 km east of Dawson City in the foothills of the Ogilvie Mountains and along the northeastern boundary of the Tintina Trench (Fig. 1). In this area, the Tintina Fault juxtaposes Proterozoic and Paleozoic rocks of the Selwyn Basin against metamorphic rocks of the Yukon-Tanana Terrane. The dominant lithologies on the property are Paleozoic clastic sedimentary rocks of the Selwyn Basin that are described by Diment, (1996), Diment and Craig (1999), and Lindsay et al. (1999), and are only briefly mentioned below. The stratigraphically lowest unit consists of Cambrian to Upper Devonian Road River Group, which includes tan-weathering, wispy laminated siltstones of the Steel Formation with interbeds of graphitic shale and chert. These rocks overlie massive black chert of the Duo Lake Formation and calcareous andesite flows, tuffs and breccias similar to the Menzie Creek volcanic rocks. A conglomerate unit deposited at the top of the sequence consists of fragments of volcanic rock in a tuffaceous or calcareous matrix. The top of the Road River Group is marked by wispy laminated siltstone. An unconformity separates the Road River Group from the Devonian-Mississippian Earn Group that is made up of a heterogeneous package of rocks including shale, black graphitic argillite, greywacke, tuffaceous chert and conglomerate, overlain by a sequence of tuffaceous sandstone and shale. Minor units include limestone and bedded barite. Sills and dykes of quartz-monzonite to syenite, belonging to the mid-Cretaceous Tombstone Plutonic Suite (Diment and Craig, 1999), intrude the deformed and faulted Paleozoic stratigraphy (Fig. 1).

The most important structures in the property area are a series of imbricated, low-angle faults that strike west-northwesterly and dip to the south. These are inferred to be thrust faults (Diment and Craig, 1999; Lindsay et al., 1999, 2000) that subsequently endured left-lateral wrench, then extensional movement. These faults may have served as fluid pathways and thus host the bulk of the mineralization.

Mineralization occurs as numerous ore bodies along a 12-km structural corridor (Fig. 1). Ore bodies consist of pyrite, arsenopyrite, and, to a lesser extent, marcasite within quartz veinlets and disseminated in areas of pervasive silicification, as well as in veins in the more competent sedimentary units (Diment and Craig, 1999). In addition, chalcopyrite, sphalerite, pyrrhotite, and late



**Figure 1.** Location map of the study area showing sampling locations, stream traces, and local geology at the Brewery Creek mine, central Yukon. Modified from Lindsay et al., 2000.

stage stibnite are present in trace amounts. In hypogene ores, gold occurs as a refractory phase in arsenian pyrite. However, since this area was not glaciated during the most recent ice advance, oxidation locally extends to depths of 100 m below surface. Consequently, the near-surface sulphide minerals have been converted to goethite and scorodite, and gold has been liberated, thus making the ores appropriate for heap leaching (Diment, 1996; Diment and Craig, 1999). Mining of the oxide ores occurred from 1995 to 2002, and recently ceased during

a time of low gold prices. The current deposit landscape is a series of open pits, haul roads and trenches.

### SAMPLING LOCATION, TECHNIQUE AND ANALYTICAL METHODS

Two seeps and three streams were sampled to define the post-mining water chemistry above and below mined-out ore zones. Sampling locations were carefully chosen so as

to best determine changes in water chemistry from just upstream of a mineralized zone (i.e., above the Lucky pit) to within a mineralized zone (i.e., immediately below the Lucky pit and below the Blue Zone), and significantly downstream from the mineralized zones (e.g., downstream of the heap leach facility and pumping facility; Table 1, Fig. 1). Field parameters, including temperature (°C), pH, dissolved oxygen (DO), and specific electrical conductance (SEC), were taken on-site using a hand-held Fisher Accumet™ all-in-one meter with the appropriate probe submerged directly into the flowing water (Fig. 2). Samples of the water were collected using a portable peristaltic pump and flexible, non-reactive, 0.635-cm-diameter tubing. For the filtered samples, a 0.45-micron nitrocellulose canister filter was attached to the delivery end of the tubing. The collected samples include: 1) a 125 ml, filtered (0.45 mm), acidified (pH~2, nitric acid) sample for inductively coupled plasma-mass spectrometry (ICP-MS), and inductively coupled



**Figure 2.** Authors sampling at location BC05-02 next to the pump house. In the foreground, pH, DO and SEC measurements are being taken. In the background, the samples are being collected.

**Table 1.** Field number and location description of the sampling sites for this study.

Field no.	Location description
BC01-02	north-trending tributary above Lucky pit, 1 m wide, maximum depth 20 cm
BC02-02	southeast below Lucky pit, junction of two tributaries, same tributary as BC01-02 but below Lucky pit
BC03-02	southeast below Lucky pit second tributary draining from Lucky pit
BC04-02	Laura Creek below Blue Zone, but not draining pit, below old exploration camp
BC05-02	Lower Laura Creek, below pumphouse, near Earn Group shale outcrop

plasma-atomic emission spectrometry (ICP-AES) analyses; 2) a 125 ml unfiltered, acidified (pH ~2) sample for ICP-MS and ICP-AES analyses; and 3) a 250 ml, unfiltered-unacidified sample for ion chromatography (IC) and alkalinity analyses. The filtered acidified sample was preserved with concentrated nitric acid after filtration, to avoid dissolving suspended particulate matter >0.45 µm in diameter.

Major, minor and trace element analyses included ICP-MS (Lamothe et al., 2002), ICP-AES (Briggs et al., 2002) and IC (Theodorakos, 2002) methods and were performed at the U.S. Geological Survey in Denver, CO, U.S.A. (Table 2). Quality control samples included field blanks, field duplicates, analytical blanks, and analytical blinds, as well as a number of certified water quality standards (Taggart, 2002).

## STREAM CHEMISTRY OUTSIDE THE ORE ZONE

Sample BC01-02 was collected from a tributary upstream of the Lucky pit and presumably above any of the mineralized zones. Analysis of this sample was intended to define the background concentrations of dissolved species in natural waters of the area that had not interacted with the hydrothermal mineralization. The water from this background site had a pH of 7.9, was strongly oxidized (DO=8.1), had a relatively high total dissolved load (SEC=403), and was Ca and HCO<sub>3</sub><sup>-</sup> dominated. It had a characteristic major element/anion composition of Ca>Mg>Na≥K and HCO<sub>3</sub><sup>-</sup>>SO<sub>4</sub><sup>2-</sup>>NO<sub>3</sub><sup>-</sup>>Cl≥F<sup>-</sup> (Table 2). Dissolved and total concentrations, respectively, were 53 and 58 mg/L Ca and 20 and

**Table 2.** Field number, location (latitude/longitude in decimal degrees<sup>1</sup>), field parameters, and selected analyses of the five water samples taken for this study.

Field no.	BC01-02		BC02-02		BC03-02		BC04-02		BC05-02	
Date	07/19/02		07/19/02		07/19/02		07/19/02		07/19/02	
Latitude	64.066667		64.05		64.05		64.033333		64.016667	
Longitude	-138.1667		-138.167		-138.167		-138.25		-138.283	
T (°C)	2.7		4.8		2.6		4.8		5.4	
pH	7.9		8.2		7.6		8		8.2	
DO (mg/L)	8.1		10.9		10.2		11.5		11.9	
SEC (µS/cm)	403		450		686		478		420	
FILTRATION	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered
Concentration (mg/L)	dissolved	total	dissolved	total	dissolved	total	dissolved	total	dissolved	total
Ca	53	58	61	65	84	62	38	49	56	61
Mg	20	21	22	24	36	27	14	17	20	22
Na	0.94	0.72	0.89	1.1	1.2	0.91	0.95	1.2	2.3	2.7
K	0.65	0.61	0.74	0.97	1.2	0.94	0.98	1.4	1.2	1.3
Fe	0.03	0.03	<0.02	0.18	<0.02	0.025	0.051	9.6	0.1	0.21
SiO <sub>2</sub>	6.8	6.6	6.6	7.3	6.0	3.9	4.5	18.0	9.0	8.8
HCO <sub>3</sub> <sup>-</sup>	181		192		182		169		156	
SO <sub>4</sub> <sup>2-</sup>	63		81		200		85		90	
NO <sub>3</sub> <sup>-</sup>	2.1		2.4		9.3		0.6		0.5	
PO <sub>4</sub>	< 0.01		0.06		< 0.01		0.12		0.09	
Cl <sup>-</sup>	0.2		0.3		0.2		0.5		0.3	
F <sup>-</sup>	0.2		0.2		0.3		0.2		0.2	
(µg/L)										
Al	3.2	17	2.3	56	1.5	9.7	16	3800	28	49
As	2	2	18	26	10	8.2	3	47	3	3
Ba	61	63	79	106	46	39	52	456	63	74
Bi	< 0.05	< 0.005	< 0.05	< 0.005	< 0.05	0.007	0.1	< 0.005	< 0.05	< 0.005
Cd	< 0.02	< 0.02	0.02	0.06	0.03	0.02	0.09	2.2	0.04	0.04
Co	0.08	0.06	0.05	0.12	0.07	0.06	0.18	7.1	0.18	0.22
Cr	1.3	< 1	5.9	< 1	< 1	< 1	4.7	7.1	6.3	< 1
Cu	< 0.5	0.54	0.71	1.1	< 0.5	< 0.5	1.5	17	1.5	1.8
Li	2.4	2.9	1.4	2.5	2.9	4.1	4	10	8	11
Mn	21	23	0.6	8.1	0.8	2.2	40	880	27	31
Mo	0.45	0.66	3.3	3.1	0.77	0.79	1.3	0.86	2.3	2.8
Ni	1.6	1.2	1.1	1.9	2.9	2	2.4	26	2.8	3
Pb	< 0.05	< 0.05	< 0.05	0.7	< 0.05	0.2	0.1	8.9	< 0.05	< 0.05
Sb	0.31	0.47	18	21	19	12	16	17	9.2	9.9
Se	4.1	3.3	3	2.3	6.8	3.6	1.9	2.5	1.8	1.7
Sr	210	240	258	338	402	357	192	302	256	319
Ti	0.6	0.9	0.6	2.1	1.7	1.6	0.5	25	0.9	2.4
U	0.55	0.53	1.2	1.2	2.3	1.6	1.35	2.4	1.7	1.7
V	0.5	0.2	1.9	0.4	0.2	< 0.1	1.5	22	2.2	0.6
W	0.24	0.09	0.2	0.1	0.38	0.22	0.08	0.05	0.2	0.07
Zn	0.6	0.6	0.6	2.2	2	1	24	128	2	3.1

<sup>1</sup>GRS 1886, NAD 27

DO=dissolved oxygen

SEC=specific electrical conductance

21 mg/L Mg; the concentrations of anions were 181 mg/L  $\text{HCO}_3^-$  and 63 mg/L  $\text{SO}_4^{2-}$  (Table 2).

Trace elements characteristic of epizonal gold deposits (e.g., Brewery Creek) that are of environmental and exploration interest include arsenic, copper, mercury, lead, antimony and zinc. Mercury concentrations were not determined during this preliminary study because an additional sample, with special preservation requirements, would have been necessary. However, the dissolved concentrations of arsenic, copper, nickel, lead, antimony and zinc were determined as 2 µg/L, <0.5 µg/L, 1.6 µg/L, <0.05 µg/L, 0.31 µg/L and 0.6 µg/L, respectively. Total concentrations of these elements were only slightly higher by, on average, <10%. Minor elements of interest, including aluminum, iron and manganese were determined because they may represent sources and sinks of trace metals associated with the mineralization in the form of colloidal oxides and hydroxides ( $\text{AlOH}_3$ ,  $\text{FeOOH}$ ,  $\text{MnOOH}$ ). These have the potential to sorb or release trace metals into the environment with changes in the pH and oxidation/reduction potential of the ground and surface water. The background dissolved concentrations of aluminum, iron and manganese were 3.2 µg/L, 0.03 mg/L and 21 µg/L, respectively, and the total concentrations were the same or slightly higher at 17 µg/L, 0.03 mg/L and 23 µg/L respectively (Table 2).

## SEEP AND STREAM CHEMISTRY WITHIN THE ORE ZONE

Two samples were collected from flow emanating from the bottom of the Lucky pit. Sample BC02-02 was taken along the same stream as sample BC01-02, about 300 m downstream from the background sample site, beyond where the stream re-emerged from beneath excavated pit rocks. Sample BC03-02 was taken from a small seep less than a metre away from BC02-02, which was flowing from eroded and mined overburden along one of the side walls of the main stream.

Significant changes occur in the water chemistry over the short distance between sites BC01-02 and BC02-02. Most notable are an increase in the dissolved and total concentrations of arsenic and antimony. Prior to entering the mineralized zone of the Lucky pit, the stream water was observed to have dissolved and total arsenic concentrations below detection limits (< 3 µg/L) and dissolved and total antimony concentrations of < 1 µg/L (Table 2). However, after interaction with mineralized

regolith removed from the Lucky pit, and presumably mineralized rock within the Lucky pit itself, the stream water showed an increase in both dissolved ( $\text{As}_{\text{diss}}$ ) and total arsenic (and  $\text{As}_T$ ) and antimony ( $\text{Sb}_{\text{diss}}$  and  $\text{Sb}_T$ ) concentrations.  $\text{As}_{\text{diss}}$  increased to 18 µg/L and  $\text{As}_T$  increased to 26 µg/L, with  $\text{Sb}_{\text{diss}}$  and  $\text{Sb}_T$  in sample BC02-02 increasing to 18 and 21 µg/L, respectively. Dissolved iron and aluminum concentrations remained at background levels, but the total iron and aluminum concentrations increased to 0.18 mg/L and 56 µg/L respectively. Surprisingly, the dissolved and total manganese concentrations decreased significantly ( $\text{Mn}_{\text{diss}}=0.6$  µg/L and  $\text{Mn}_T=8.1$  µg/L) after the waters had interacted with the mineralized rock. In contrast, the major element/anion abundances, pH, DO, and SEC remained relatively unchanged, differing by <10% from the upstream background values.

Sample BC03-02 also showed elevated trace element concentrations ( $\text{As}_{\text{diss}}=10$  µg/L,  $\text{As}_T=8.2$  µg/L and  $\text{Sb}_{\text{diss}}=19$  µg/L,  $\text{Sb}_T=12$  µg/L). Dissolved and total aluminum and iron concentrations are low and similar to those of BC01-02. Dissolved and total manganese concentrations are similar to those of BC02-02 (Table 2). However, the pH (7.6) is significantly lower than all other samples, the SEC (686 µS/cm) is the highest measured during the study, and the dominant anion is  $\text{SO}_4^{2-}$  (200 mg/L), rather than  $\text{HCO}_3^-$ . These differences reflect the smaller discharge from the seep below the pit that has interacted extensively with the mineralized material in the channel walls.

Sample BC04-02 collected in Laura Creek, and taken below the Blue Zone, also shows evidence of interactions with mineralized rock as indicated by elevated arsenic and antimony concentrations ( $\text{As}_{\text{diss}}=3$  µg/L,  $\text{As}_T=47$  µg/L and  $\text{Sb}_{\text{diss}}=16$  µg/L,  $\text{Sb}_T=17$  µg/L). In addition to the arsenic and antimony, sample BC04-02 also shows increased copper, nickel, lead and zinc concentrations ( $\text{Cu}_{\text{diss}}=1.5$  µg/L,  $\text{Cu}_T=17$  µg/L;  $\text{Ni}_{\text{diss}}=2.4$  µg/L,  $\text{Ni}_T=26$  µg/L;  $\text{Pb}_{\text{diss}}=0.1$  µg/L,  $\text{Pb}_T=8.9$  µg/L; and  $\text{Zn}_{\text{diss}}=24$  µg/L,  $\text{Zn}_T=128$  µg/L) suggesting, not only interaction with arsenic- and antimony-bearing sulphide and oxide minerals, but also minor base metal sulphide minerals that are sometimes recognized in the ore zones. Furthermore, both total and dissolved aluminum, iron and manganese ( $\text{Al}_{\text{diss}}=16$  µg/L,  $\text{Al}_T=3800$  µg/L;  $\text{Fe}_{\text{diss}}=0.051$  mg/L,  $\text{Fe}_T=9.6$  mg/L;  $\text{Mn}_{\text{diss}}=40$  µg/L,  $\text{Mn}_T=880$  µg/L) concentrations are the highest among all samples in this study.

Given the relatively high DO concentration of all the water samples, the most probable mechanisms controlling the mobility of arsenic and antimony is the oxidation of the primary sulphide minerals (i.e., arsenopyrite and stibnite), or the dissolution of their secondary weathering products (i.e., scorodite and stibiconite). Studies have shown that at neutral to alkaline pH, the oxidation of arsenopyrite can lead to substantial dissolved arsenic concentrations ( $> 1$  mg/L; Craw et al., 2003). The amount of arsenic entering into solution is limited by the formation of iron-oxide coatings on the arsenopyrite grains and thus the amount of arsenic actually released can be orders of magnitude less than predicted by equilibrium values ( $< 0.1$  mg/L; Smedley and Kinniburgh, 2002; Craw et al., 2003). Furthermore, given that the ore bodies may be oxidized to depths of several tens, if not up to 100 m depth, it is likely that the dissolution of scorodite, which is not stable at high pH is the source of the arsenic in the groundwater (Krause and Ertle, 1988; Vink, 1996). During both oxidation of arsenopyrite and dissolution of scorodite, acidity is produced. However, as supported by the pH measurements (Table 2), there appears to be ample buffering capacity within the Brewery Creek deposit. Mapping and Portable Infrared Mineral Analyser (PIMA) studies by Viceroy Resources recognized an ankeritic alteration halo to the mineralized rock which has contributed to this buffering. Similarly, the oxidation of stibnite, or dissolution of stibiconite, is the most likely source for the elevated dissolved antimony concentrations (Filella et al., 2002).

## STREAM CHEMISTRY DOWNSTREAM OF THE ORE ZONE

Sample BC05-02 was taken from lower Laura Creek, near the location of the pump house, downstream of the heap leach facility (Figs. 1 and 2) and 2 km downstream from the recognized mineralized rock and site BC04-02. This site is interpreted to include the surface water that has flowed through the bulk of the ore zones to the north and possibly through non-mineralized bedrock on the southern side of the deposit, and is consequently diluted within the larger Laura Creek (Fig 1). Arsenic concentrations have been diluted from elevated levels at BC04-02 to near detection limits ( $3$   $\mu\text{g/L}$ ) in the surface waters at site BC05-02. Total and dissolved copper, lead, nickel and zinc concentrations are also only slightly enriched or at background levels. The major elements and anions, pH, DO, and SEC are all similar to the observed

values at site BC01-02. In contrast, dissolved and total antimony have stayed relatively high ( $\text{Sb}_{\text{diss}} = 9.2$   $\mu\text{g/L}$  and  $\text{Sb}_T = 9.9$   $\mu\text{g/L}$ ). The total and dissolved aluminum, iron and manganese concentrations are still elevated compared to those at BC01-02, although diluted to only about 50% of their concentrations in the mineralized zones (samples BC02-02, BC03-02 and BC04-02, Table 2).

The increase in the mineralized zone, and subsequent downstream decrease in concentrations of aluminum, iron and manganese, play an important role in the sequestration of most trace metals (arsenic, copper, zinc). This is due to the formation of iron, aluminum and manganese hydroxides which, in oxidizing conditions, create colloids that adsorb the trace metals and precipitate out of the water column (Driehaus et al., 1995; Manning and Goldberg, 1997; Raven et al., 1998; Smedley and Kinniburgh, 2002). The persistence of elevated dissolved antimony in waters away from the mineralized zone can likely be explained by the fact that antimony can form potentially non-reactive anionic species ( $\text{Sb}(\text{OH})_6^-$ ) and remain in solution (Vink, 1996; Filella et al., 2002). In contrast, arsenic concentrations decrease rapidly downstream because iron, manganese, and possibly aluminum hydroxides adsorbed/absorbed the arsenic onto/into their structure and precipitated out of solution.

## COMPARISON TO OTHER TGP EPIZONAL DEPOSITS

A comparison of the arsenic and antimony concentrations in surface and subsurface waters from Brewery Creek with similar style epizonal deposits at the True North and Donlin Creek deposits, although in different stages of development, shows that the arsenic-antimony hydrogeochemical signature characterizes the waters draining all of these systems (Table 3; Mueller et al., in press). The arsenic concentrations in water within the mineralized zones, regardless of stage of development, average  $29$   $\mu\text{g/L}$  for all three deposits, and the total antimony concentration in the same areas average  $9.3$   $\mu\text{g/L}$  (Table 3). Outside of the deposit, both arsenic and antimony concentrations drop off to normal background concentrations of  $2.7$  and  $0.204$   $\mu\text{g/L}$  respectively at Donlin Creek, and  $2.5$  and  $5.1$   $\mu\text{g/L}$  at Brewery Creek (Table 3).

**Table 3.** Comparison of the minimum, maximum, and average total arsenic and antimony concentrations within and outside of the Brewery Creek (post-development), True North (in development), and Donlin Creek (pre-development) epizonal gold deposits.

Deposit	Element	Concentration within mineralized zone (µg/L) <sup>1</sup>				Concentration outside of mineralized zone (µg/L) <sup>2</sup>			
		minimum	maximum	average	n	minimum	maximum	average	n
Donlin Creek	As	<3	274	33	15	<1	4.7	2.7	13
	Sb	<0.1	4.5	1.5		<0.1	0.35	0.204	
*True North <sup>3</sup>	As	17	42	26	6				
	Sb	2.5	20	9.5					
Brewery Creek	As	8.2	47	27	3	2	3	2.5	2
	Sb	12	21	17		0.47	9.9	5.1	
Donlin Creek, True North, Brewery Creek	As			29	24			2.6	15
	Sb			9.3				2.7	

<sup>1</sup>samples taken within resource area or mapped mineralization  
<sup>2</sup>samples take outside of known mineralized area  
<sup>3</sup>all streams sampled in the vicinity of True North emanate from the mineralized area, therefore there is no outside information available  
\*True North data is part of a larger unpublished dataset

## CONCLUSIONS AND FUTURE WORK

Preliminary reconnaissance studies of the current background hydrogeochemistry of the post-mining environment at the Brewery Creek mine reveal:

- The natural streams and seeps outside of known mineralization and within the mineralized area are naturally alkaline (pH 7.6-8.2) Ca-HCO<sub>3</sub><sup>-</sup> to Ca-SO<sub>4</sub><sup>2-</sup> type waters;
- Elevated arsenic, copper, antimony and zinc concentrations are the result of either oxidation of primary sulphide minerals, or the dissolution of secondary oxidation products, with no net acidification, likely due to buffering by host rocks;
- The production of aluminum, iron and manganese hydroxides during oxidation or dissolution of primary sulphide minerals or secondary minerals may sequester the trace metals arsenic, copper and zinc, effectively reducing their mobility;
- Antimony appears to remain in solution, despite the presence of possible sorbents (Al-, Fe-, Mn- hydroxides) most likely as a consequence of the high pH and oxidizing conditions of the surface water;

- The post-mining hydrogeochemical signatures at Brewery Creek are similar to both undeveloped Donlin Creek and the developing True North deposits in Alaska, showing that low-level concentrations of As, Sb and other metals are naturally typical of waters draining these epizonal deposits, regardless of whether they are developed or not.

At the time of writing, sulphur isotope analyses on aqueous sulphate are currently being performed in order to determine whether a distinct sulphur isotope signature for the gold-bearing sulphide minerals can be detected, in the hope that this will provide another exploration tool with which to prospect for additional epizonal deposits in the Tintina Gold Province. Further study of trace element arsenic, antimony and mercury (As, Sb, and Hg) mobility in the surface environments at these deposits will contribute to the development of a geoenvironmental model useful for the exploration and development of these deposits in the future.

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