Metal Leaching in a Neutral pH Environment: EKATI Diamond Mine, NT, Canada

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ABSTRACT

Waste rock piles at EKATI Diamond mine are dominated by distinct very low sulphur waste rock types. Average total sulphur is 0.02 to 0.05 % for granitoid rocks, 0.2% for biotite schist, 0.1% for diabase and 0.2 to 0.4% for waste kimberlite, depending on the pipe. Carbonate content is also negligible with the exception of waste kimberlite. Drainage chemistry reflects weathering of silicate minerals and minor sulphides, in addition to carbonates in kimberlite, under cold and arid conditions. Major and trace element chemistry in waste rock storage area seepage (with over 10 years of monitoring), can be related to the distinctive mineralogy of the waste rock and allows different water sources to be recognized. The Mg/Ni ratio is a key indicator of the main influences on seepage chemistry at EKATI. Mg/Ni is very high in kimberlite seepage (up to 30,000) and low in seepage from biotite schist (down to 140). Mg/Ni in seepage dominated by a granitoid or tundra source is approximately 500 to 800.

Key Words: Mg/Ni ratio, waste rock seepage, kimberlite, sulphide oxidation, weathering, silicates

INTRODUCTION

BHP Billiton Canada Inc. has been mining diamonds by open pit methods from six kimberlite pipes at the EKATI Diamond Mine (EKATI) since 1998. The kimberlites are hosted by igneous and metamorphic rocks of the Archean Slave Craton. Waste is contained within three waste rock storage areas (WRSAs; Panda-Koala, Fox and Misery; Figures 1 to 3). Waste rock is dominated by granite, with lesser amounts of waste kimberlite, coarse kimberlite reject, biotite schist and small amounts of diabase. The WRSAs are in a partially frozen state with permafrost aggradation playing a role in their chemical stability.

Seepage waters from the WRSAs have been monitored since 1999. With the exception of mildly acidic waters resulting from interaction with the naturally acidic tundra (Day et al, 2003), the majority of data demonstrate neutral pH drainage. The seepage monitoring data provide detailed, long-term, valuable information on the chemical signature of water interacting with distinctive very low sulphur and generally low carbonate (except for kimberlite) waste rock types. Drainage chemistry from the host rocks reflects weathering of silicate minerals and minor sulphides under very cold and arid climatic conditions. Mean annual temperature is -11°C (range of -50 to +30°C) and annual total precipitation is 300 mm.

This paper reviews chemistry data for selected seeps in the Panda-Koala and Misery areas, with many years of data, which illustrate the range of waters observed from EKATI WRSAs. Major and trace element concentrations in the seeps can be related to the distinctive mineralogy of the waste rock and allow different water sources to be recognized. A key indicator of differences in seepage chemistry is the magnesium-nickel ratio (Mg/Ni). This study has implications for future WRSA design and allows for more informed adaptive management practises.

BACKGROUND

Waste Rock Storage Area Design and Construction

The WRSAs were designed to limit seepage and promote freezing within the piles. In addition, potentially reactive materials (such as biotite schist) have been encapsulated by low reactivity granitoid rocks which have been placed in zones expected to be subject to seasonal thawing, so that potentially reactive materials remain frozen. Seepage from the WRSAs occurs during freshet and through the short summer.

Figure 1. Location of the EKATI Diamond Mine.

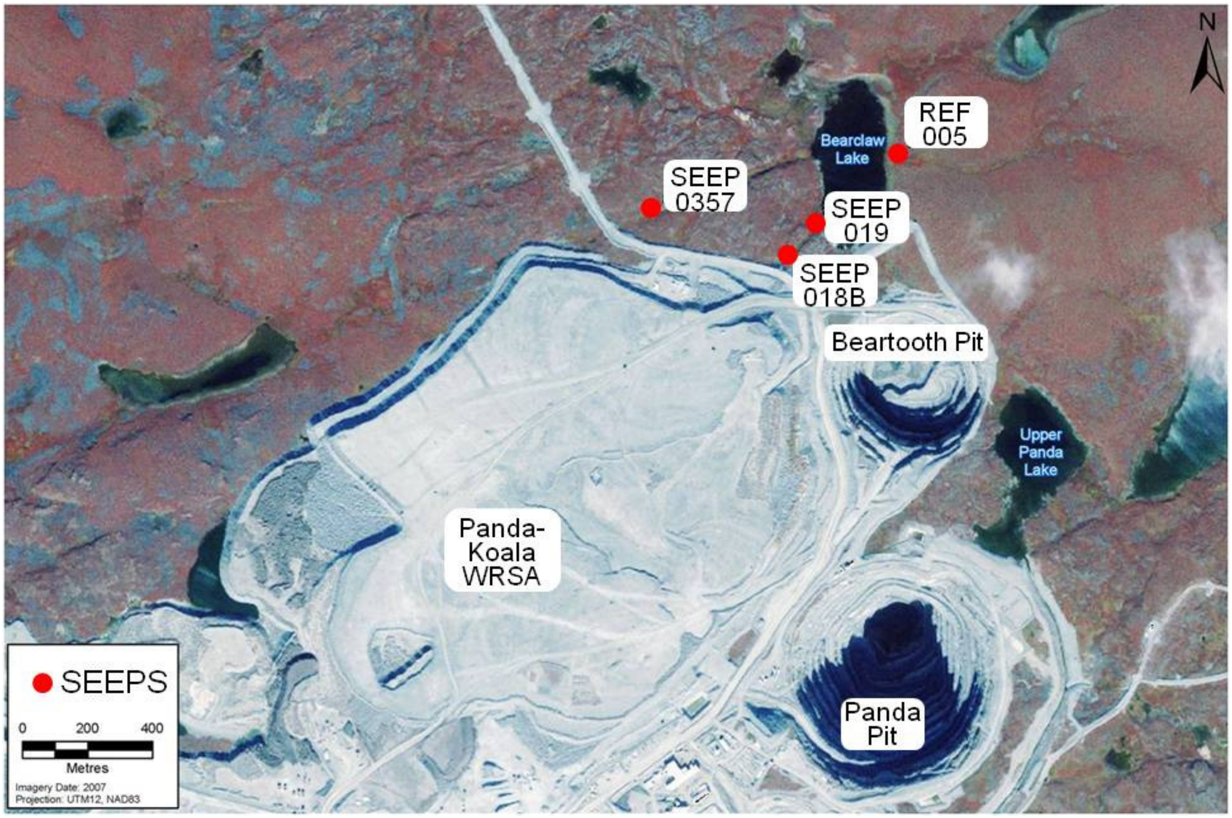

Figure 2. Panda-Koala NE Waste Rock Storage Area and Location of Seeps and Reference Station.

Figure 3. Misery Waste Rock Storage Area and Location of Seeps.

Panda-Koala WRSA
The Panda (1998-2004), Koala (2003-2005), Koala North (2001-2003) and Beartooth (2004-2009) pits have all provided waste rock to the Panda-Koala WRSA. Although Koala and Koala North are still being mined underground, they are no longer contributing waste rock to the WRSA. The WRSA can be divided into a north eastern section (Panda-Koala NE) containing granitic waste rock with minor amounts of waste kimberlite (Figure 2), and a south western section containing granite and waste kimberlite, in addition to coarse (0.5 to 25 mm) processed kimberlite rejects from all six kimberlite pipes (Coarse Kimberlite Reject Storage Area-CKRSA). Seepage waters from the majority of the Panda-Koala WRSA drain or are collected and pumped, into the Long Lake Containment Facility (LLCF, Figure 1).

MISERY WRSA
The Misery pit is approximately 30 km to the south east of the Panda-Koala area. Mining at Misery occurred from 2000 to 2005. The Misery WRSA contains potentially ARD generating biotite schist encapsulated within granite and minor diabase. A 5 m thick granite cap was placed over the WRSA in 2005 to maintain the active freeze-thaw zone within granite, hence minimizing potential sulphide oxidation within the schist.

Other storage areas at Misery include the Temporary Kimberlite Ore Storage Area and the Waste Kimberlite Storage Area (Figure 3). Neither of these are in use but both contain residual kimberlite. The majority of seepage from the Misery WRSA reports to approved containment facilities (Desperation Pond, King Pond). Seepage from the Temporary Kimberlite Ore Storage Area flows to Cujo Lake via SEEP-081 discussed below. Seepage from the east side of the WRSA towards Lac de Gras is limited by a dam. A seep of interest at Misery is SEEP-052 (Figure 3). Mixed kimberlite and schist was temporarily placed upstream of this seep causing increased metal leaching discussed in subsequent sections.

Geology, Geochemistry and Weathering of Waste Rock
The mineralogical characteristics in this section are summarized from Norecol, Dames and Moore (2007) and ABA characteristics from SRK Consulting (2007). Quartz diorite to granite dominates in the WRSAs, comprising over 90 % of the total waste rock volume. It is composed predominantly of plagioclase feldspar, biotite and quartz with lesser alkali feldspar. Minor components are mafic minerals (amphibole, chlorite, epidote), muscovite, sericite and titanite. Trace amounts of calcite, apatite, chalcopyrite, tourmaline and pyrite may also be present. Average total sulphur for granite is 0.02 to 0.05 % depending on the area, and ABA has shown the granites to be not potentially ARD generating.

Biotite schist is a major component in the Misery WRSA. The rock is dominated by plagioclase, biotite and quartz. Potassium feldspar, muscovite, chlorite and sericite occur as minor components with trace amounts of silliminite, pyrrhotite, ilmenite, rutile, apatite and tourmaline also occurring. Average total sulphur for biotite schist is 0.2 %. Kinetic testing in humidity cells has shown that the biotite schist generates acidity under laboratory conditions but ARD has not been observed at the site.

Waste kimberlite has highly variable composition but generally includes olivine, phlogopite, serpentine, calcite, dolomite, chlorite, spinel, chrome diopside, garnet, quartz and trace amounts of pyrite. Average total sulphur for waste kimberlite is 0.2% at Misery, 0.35% at Fox and 0.3% at Koala, and ABA has shown that waste kimberlite is non-ARD generating.

Diabase occurs in small amounts at Misery. It is a competent rock type dominated by plagioclase, clinopyroxene and amphibole, with minor chlorite, magnetite, sericite and biotite. Trace titanite, potassium feldspar, pyrrhotite and pyrite may also occur. Average total sulphur for diabase at Misery is 0.1% and it is non-ARD generating.

Leaching Processes
Based on the mineralogical characteristics of non-kimberlite waste rock (quartz diorite-granite, biotite schist and diabase), the dominant weathering mechanism is expected to be reaction of dissolved carbon dioxide (carbonic acid) with silicate minerals, for example:

Plagioclase: $NaAlSi_3O_8 + H_2CO_3 + 7H_2O \rightarrow Na^+ + Al(OH)_3 + HCO_3^- + 3H_4SiO_4$

Biotite (Phlogopite): $KMg_3AlSi_3O_{10}(OH)_2 + 7H_2CO_3 \rightarrow K^+ + 3Mg^{2+} + Al(OH)_3 + 7HCO_3^- + 3H_4SiO_4$

Silicate weathering reactions are expected to proceed extremely slowly. Intermediate weathering products such as vermiculite from breakdown of biotite are also expected. Oxidation of small amounts of sulphides is expected to occur resulting in leaching of sulphates and trace heavy elements. Kimberlite weathering is expected to be dominated by reaction of carbonic acid with carbonates, secondary sulphates and silicates, resulting in leaching of alkali earth metals, for example:

Calcite: $CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$

Dolomite: $MgCa(CO_3)_2 + 2H_2CO_3 \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-$

Olivine: $Mg_2SiO_4 + 2H_2CO_3 + H_2O \rightarrow Mg^{2+} + H_4SiO_4 + 2HCO_3^-$

Available mineral-melt partition coefficient data (e.g. Ewart and Griffin 1994) can be used to indicate likely trace element substitutions in silicate minerals to allow an understanding of observable trace element characteristics in drainage chemistry.

Some metals are relatively insoluble at near-neutral pH, such as Al, Fe and Cu (Price 2009). However their dissolution may be increased if they bond with organic acids as may happen within soils of the tundra. This can affect drainage chemistry for seeps that flow through the tundra.

Mg-Ni Ratio
Magnesium and Ni occur at relatively elevated concentrations in primitive rocks relative to evolved rocks. This is because primitive rocks (including kimberlite) are rich in olivine, and Ni is compatible within the crystal structure of olivine.

The Mg-Ni characteristics of felsic crust are quite different. Mg is hosted in minor phases such as biotite and amphibole, and Ni is less compatible in these minerals. Ni content is therefore typically low in felsic rocks. Nickel is however highly compatible in sulphide minerals, so their presence can increase the Ni content of felsic rocks.

With this in mind, it was considered that Mg/Ni ratio may be a useful indicator for determining the source of seepage waters at EKATI. The Mg/Ni ratio in feslic rocks was expected to be high due to very low Ni content. The Mg/Ni ratio in kimberlite was expected to be lower due to high Mg and high Ni content. The precursor to the biotite schist is metasedimentary rocks (turbidites) derived from weathering of granitic and volcanic rocks of the Archean Slave Craton, with a range of compositions, and may therefore be expected to have Mg/Ni ratios between those of granite and kimberlite.

It was initially thought that the Mg/Ni ratio in seepage waters would reflect the Mg/Ni ratio in the source rocks. However, Mg/Ni ratios in the seepage waters are strongly controlled by the solubility of the minerals that contain Mg and Ni and thus, release from carbonates, sulphates and sulphides dominates over release from silicates. Nickel solubility is also strongly controlled by pH in the range of typical natural waters and this influences the ratio of Mg/Ni in water because magnesium is less affected by pH.

METHODS

Rock Characterization

Waste rock characterization as part of routing monitoring at EKATI has included collection of over 2000 waste rock samples during mining, and over 140 samples of coarse kimberlite reject. These have been analysed for major and trace elements by ICP-AES following a four-acid digestion, at ALS Minerals in North Vancouver, B.C.

Seepage Surveys

Seeps flowing out of the WRSAs are sampled twice each year, during freshet (typically June) and before freeze up (in September). Any new seeps are also identified and sampled by walking the perimeter of each WRSA. Only seeps with visible flow are sampled, as standing pools may not represent WRSA seepage.

Eleven reference stations have also been sampled since the program began. These are located on small streams in catchment areas not disturbed by mining. Data for station REF-005, which is 0.5 km NE of the Panda-Koala WRSA are considered in this paper. It drains the tundra from a catchment to the east.

Field measurements taken at each seep include pH, conductivity, ORP, temperature and flow. Three sample bottles are filled at each seep for anions/nutrients/physical parameters, total elements, and elements determined on a filtered sample. Sample filtration and preservation using concentrated nitric acid are performed at the time of sampling using disposable Nalgene filtration units (0.45 µm) and a vacuum hand pump. Water samples are analysed at ALS Environmental in Burnaby, BC. Quality control measures include travel blanks, method blanks and field duplicates. Results are reported bi-annually to the Wek'èezhìi Land and Water Board and are available through the on-line Public Registry.

RESULTS

Rock Characteristics

Elemental concentrations are summarized for all waste rock types from Misery, and also for Beartooth granite (Table 1). The geochemistry of Misery kimberlite and diabase are considered representative of these waste rock types from the other pits, whereas Misery and Beartooth granite encompass the range of geochemistry (particularly Mg and Ni concentrations) observed in granite from all the pits.

Quartz Diorite-Granite

Compared to kimberlite, quartz diorite-granite (termed granite for the remainder of this paper) is high in Al and Na, and low in Mg reflecting the dominant silicate mineralogy. Heavy metals such as Cr, Co and Ni are also low in granite however Cu and Zn can be similar to or significantly higher in granite than kimberlite. This reflects both the sulphide mineralogy and the presence of characteristic mineral phases in the kimberlite such as Cr-diopside and spinel. Magnesium and Ni content in the Beartooth granite is higher than that in the Misery granite. This may reflect the presence of mafic xenoliths in the Beartooth granite that are commonly observed in the waste rock pile. The median molar Mg/Ni ratio in granites from both areas is similar at 820 to 850 but can be significantly higher (95 percentile ratios of 975 in Beartooth granite and 2036 in Misery granite).

Kimberlite

Kimberlite geochemistry is compared to granite above. Of the various waste rock types Mg, Ni and Cr are highest in kimberlite. The median Mg/Ni ratio in kimberlite is approximately 300.

Biotite Schist

The schist at Misery has similar major element characteristics to granite, with the exception of lower Ca. Trace element geochemistry differs with the schist being high in As, Cu and Zn compared to granite and kimberlite; and high in Cr and Ni compared to granite. The median Mg/Ni ratio in schist is 520.

Table 1. Summary Statistics for Waste Rock from Misery and Beartooth.

Rock Type	Units	Al %	As ppm	Ba ppm	Ca %	Co ppm	Cr ppm	Cu ppm	Fe %	K %	Mg %	Mn ppm	Mo ppm	Na %	Ni ppm	Zn ppm	Mg/Ni mol/mol
Beartooth Granite (29 samples)	95th Percentile	8.9	9.2	770	3.6	29	241	65	4.3	2.5	5.2	563	3.0	2.8	314	80	975
	Median	8.1	5.0	620	3.1	16	118	28	3.3	1.9	1.8	420	1.0	2.6	49	70	848
	5th Percentile	7.4	5.0	570	2.1	14	63	9.0	3.1	1.5	1.6	320	1.0	2	44	61	413
Misery Granite (69 Samples)	95th Percentile	9.1	23	910	2.5	26	179	112	5.3	2.9	2.1	775	4.6	4.3	83	91	2036
	Median	8.0	5.0	660	1.3	3.0	78	7.0	1.0	2.0	0.34	180	1.0	3.2	9.0	42	821
	5th Percentile	6.9	1.0	420	0.83	1.0	38	2.0	0.8	1.4	0.2	132	1.0	2.3	3.0	32	405
Misery Schist (278 Samples)	95th Percentile	9.4	158	780	2.2	34	281	76	4.7	3.2	3.2	677	7.0	2.7	205	120	776
	Median	8.0	15	550	0.93	21	166	46	3.7	2.3	1.6	395	2.0	1.9	73	80	522
	5th Percentile	6.4	5.0	380	0.55	9.0	93	18	1.9	1.6	0.76	249	1.0	1.0	28	46	355
Misery Diabase (8 Samples)	95th Percentile	6.8	5.0	227	6.0	52	158	330	11	1.0	3.5	1999	1.0	2.3	77	156	1211
	Median	6.5	5.0	205	5.3	48	121	284	10	0.89	3.1	1788	1.0	2.1	65	131	1184
	5th Percentile	6.1	2.4	184	4.4	47	96	236	9.3	0.75	2.7	1559	1.0	1.9	56	112	1086
Misery Waste Kimberlite (5 Samples)	95th Percentile	5.0	14	2116	3.9	57	847	32	3.9	2.6	13	830	4.4	0.4	1007	69	331
	Median	2.6	5.0	950	3.2	52	784	23	3.6	1.1	11.5	720	1.0	0.2	939	58	310
	5th Percentile	2.1	5.0	316	1.1	32	511	16.2	2.9	0.5	7.2	315	1.0	0.1	577	39	277

Note: Values below detection were replaced by detection limits for calculation of summary statistics.

Diabase

Diabase makes up only a very small proportion of the waste rock. It is high in Ca, Fe, Cu, Mn and Zn compared to all the other waste rock types and has high Mg/Ni (approximately 1200).

SEEPAGE CHARACTERISTICS

In the following sections dissolved element concentrations are presented and discussed because they represent the load stemming from mineral weathering within the WRSAs. Total element concentrations are measured but not evaluated as they tend to represent locally-entrained suspended sediments.

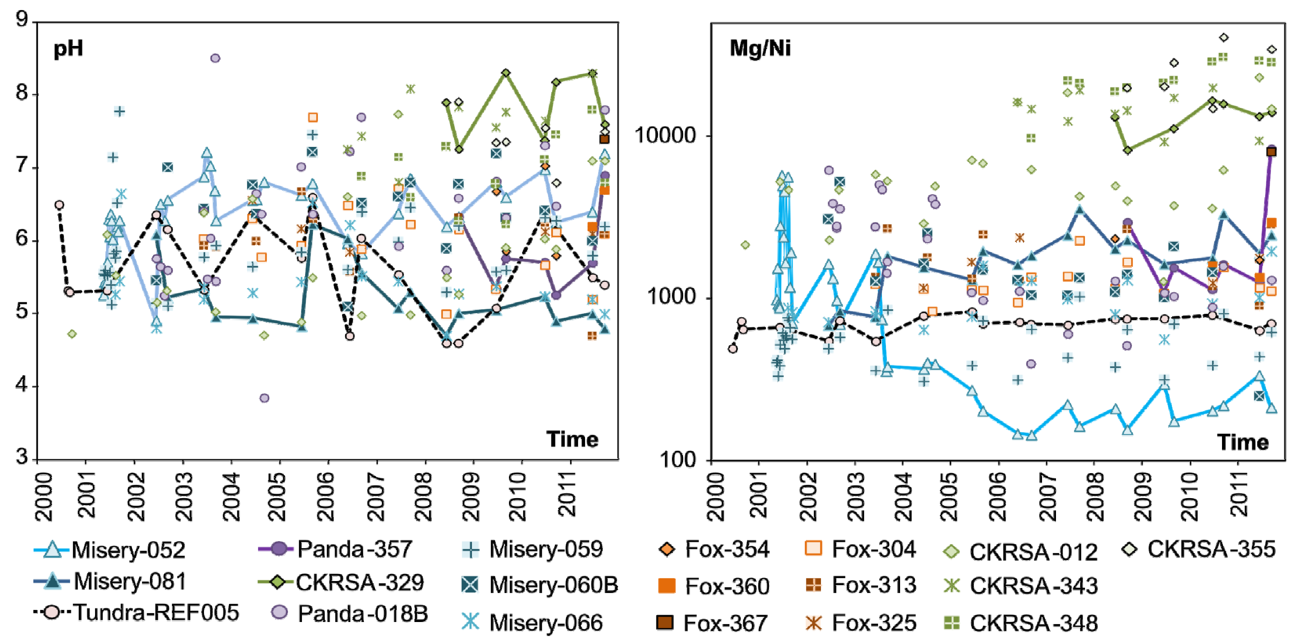

Figure 4. pH versus time and Mg/Ni versus time for key seeps at EKATI.

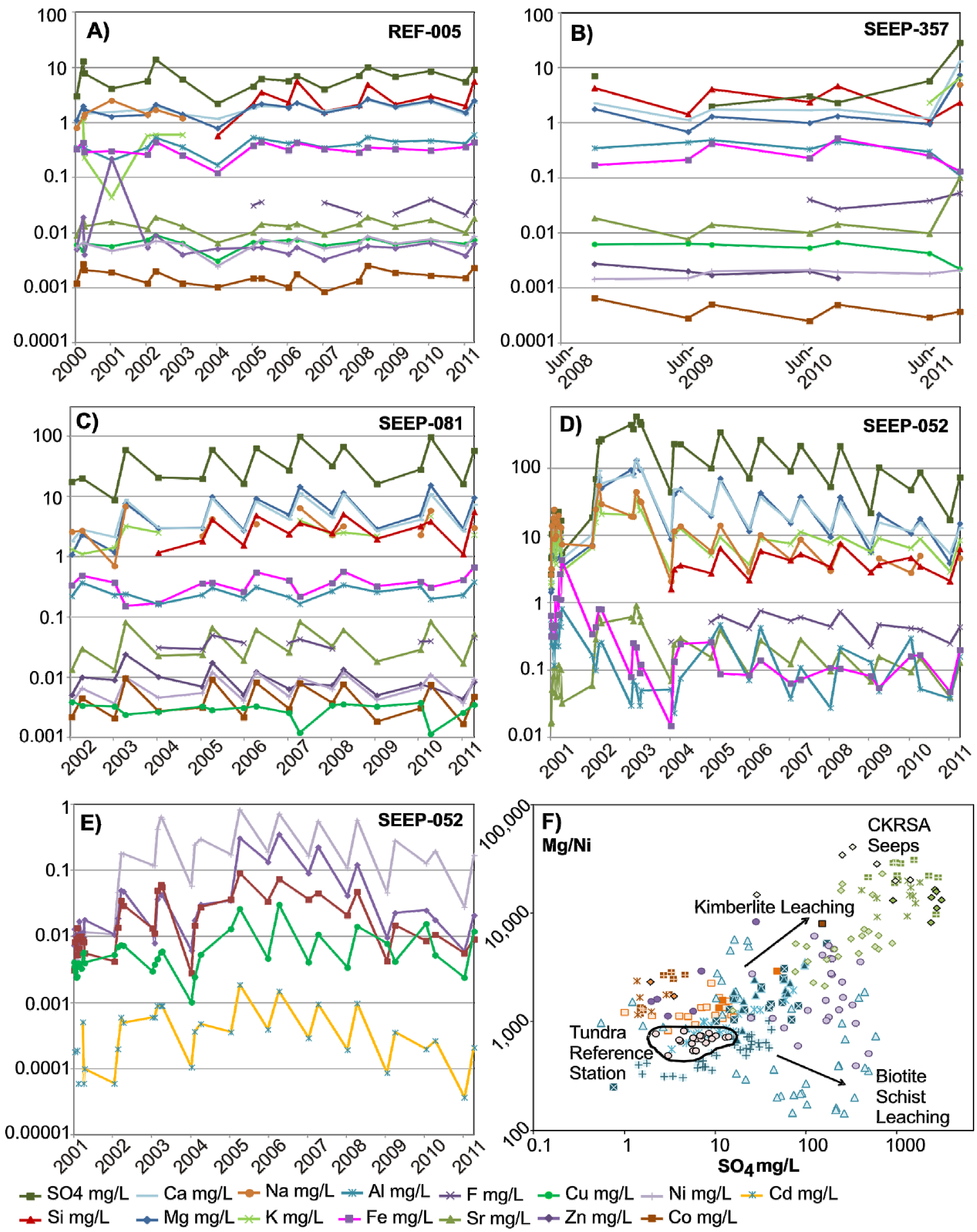

Figure 5. A) to E) Multi-parameter charts showing seepage chemistry over time for key seeps discussed in the text. F) Mg/Ni versus sulphate for main seeps at EKATI with main influences on water chemistry shown; see Figure 4 for legend.

pH vs time and Mg/Ni vs time (Figure 4) are shown for the main seeps from each WRSA. In addition, several key seeps are highlighted on these figures which are discussed in more detail in the subsequent sections. For key seeps, element concentrations are plotted on charts against time, with several parameters shown together to illustrate the chemistry and sources of each seep (Figure 5a to 5e). Figure 5f shows Mg/Ni vs sulphate for the main seeps from each of the WRSAs, to give a broader picture of the chemistry and to summarise the main processes affecting seepage chemistry at EKATI.

pH of seepage

The low pH of water in the tundra reference station (Figure 4) illustrates the pH range of waters interacting with naturally acidic tundra soils, which is also reflected in waste rock seepage that flows through the tundra for any significant distance (for example Seep-081 at Misery). Seeps that do not interact with the tundra tend to have higher pH; with those draining kimberlite storage areas having the highest pH (e.g. Seep-329 draining the CKRSA with pH 7.3 to 8.3).

Tundra Reference Station: REF-005

The field pH of water in the tundra reference station ranges from 4.6 to 6.6. Natural tundra waters are very dilute with chemistry dominated by SO_4, HCO_3 and Si at concentrations of 1 to 10 mg/L and Ca, Mg and Na at concentrations of 1 to 3 mg/L (Figure 5a). Al, Fe and K concentrations are typically 0.3 mg/L. Concentrations of Cu, Ni and Zn are typically near 0.005 mg/L. Mg/Ni ratios are 490 to 830 (Figure 4).

Panda-Koala NE WRSA: SEEP-357

Seep-357 (Figure 2) drains a granite-dominated part of the WRSA with minor kimberlite, and emerges within the tundra approximately 80 m downstream of the WRSA. With the exception of the September 2011 data, the major ion characteristics are very similar to the tundra reference station with pH of 5.3 to 6.3, HCO_3 of 3 to 6 mg $CaCO_3$/L, SO_4 up to 7 mg/L, Si up to 5 mg/L and Mg and Ca up to 2 mg/L (Figure 5b). The September 2011 data however show almost order of magnitude increases in SO_4, HCO_3, Mg and Ca and an increase in pH to 6.9 (Figure 4). Cu concentrations are similar to the reference station (close to 0.005 mg/L), whereas Ni and Zn concentrations are slightly lower than the reference station (0.001 to 0.003 mg/L). Mg/Ni ratio is typically 1100 to 2950, but 8390 in September 2011 (Figure 4).

Misery Temporary Kimberlite Ore Storage Area: SEEP-081

Seep-081 drains a kimberlite stockpile near the Misery WRSA (Figure 3). This has not been in use since 2007 but residual kimberlite sand remains. Seepage waters from here flow diffusely through the tundra for approximately 500 m before coalescing into a well-defined channel.

The field pH of water at Seep-081 ranges from 4.7 to 6.2 (Figure 4) with HCO_3 around 2 to 3 mg $CaCO_3$/L. Compared to the tundra reference station, SO_4 is elevated at 10 to 100 mg/L. Ca and Mg are also higher at 2 to 15 mg/L, whereas Si is lower at 1 to 5 mg/L (Figure 5c). Na and K are up to 6 mg/L. Al and Fe are typically 0.2 mg/L, similar to the reference station. Concentrations of Zn, Ni, Co and Cu are typically 0.001 to 0.01 mg/L. Molar Mg/Ni ratios were 680 to 840 in 2002, steadily increasing to a maximum of 3600 by September 2007, and then varying between 1630 and 3330 since then.

Misery WRSA: SEEP-052

The field pH of water in Seep-052 ranges from 4.9 to 7.2 (Figure 4). HCO_3 ranges from below DL in 2001, to a maximum of 79 mg $CaCO_3$/L in 2003. Since 2005, HCO_3 has ranged from 5 to 30 mg $CaCO_3$/L. Many major ions were similar to tundra reference concentrations in 2001 but increased rapidly to highs in 2003 and then have subsequently declined slowly. SO_4 was 0.55 to 580 mg/L. Mg and Ca were 1 to 140 mg/L, K and Na were around 1 to 50 mg/L and Si was 1 to 8 mg/L (Figure 5d, 5e). Al was higher than the reference area peaking at 0.8 mg/L in both 2001 and 2005. Significant trace ions that peaked in 2005 to 2006 are Ni up to 0.83 mg/L, F up to 0.76 mg/L, Zn up to 0.35 mg/L and Cu up to 0.03 mg/L.

At Seep-052 Mg/Ni ratios were 880 to 1540 in early 2001, increasing sharply to 5750 during the summer of 2001, then varying between 700 and 1900 from June 2002 to July 2003. Since July 2003 the Mg/Ni ratio has dropped significantly to between 140 and 400 (Figure 4).

DISCUSSION

Tundra Signature

Reference station waters show evidence of interaction with tundra soils which typically consist of organic matter and weathered granitic material (which vastly dominates over kimberlitic material). Low pH reflects weak buffering of meteoric waters by reaction with silicates, and organic decomposition. The mineral component of tundra soils is primarily granite-derived and this is reflected in:

- Si content higher than Ca and Mg, indicating a greater contribution from quartz and other felsic minerals (present in granite) rather than carbonates and mafic minerals (low in granite);
- Correlation of Al with Sr and Ba (that typically substitute into feldspars e.g. Ewart and Griffin 1994), suggesting breakdown of feldspars as their source;
- Low (<0.01 mg/L) levels of Ni, Zn, Co and Cd which are typically hosted in easily leachable sulphides, which are of low abundance in granite at EKATI; and
- Mg/Ni ratios (490 to 830) that are similar to those found in granite (Table 1).

Fe and Al concentrations of around 0.3 mg/L are higher than most seeps that do not traverse the tundra (except for Seep-052). These are a result of increased solubility at depressed pH's but may also be due to colloids and high molecular weight organic complexes passing through the filtration unit.

Granite Waste Rock Signature

Several seeps including Seep-357 drain granitic waste rock and have concentrations of many parameters that are very similar to the tundra reference station (Figure 5a, b). All these seeps also travel through the tundra for some distance and hence the water interacts with tundra soils. Distinguishing between these two signatures is therefore difficult. It is likely that the granite waste rock signature and the tundra signature are similar as both are primarily derived from interaction with the same mineral components.

Kimberlite Signature

As observed in CKRSA seepage, the main products of kimberlite leaching are SO_4, Ca and Mg from relatively soluble carbonates and secondary sulphates. Secondary to this overwhelming signature may be Mg, Si and Ni from silicates such as olivine and serpentine, and K and Na from phlogopite mica.

High Mg/Ni ratio is also indicative of kimberlite leaching; seeps draining the CKRSA have Mg/Ni ratios in the range 8,000 to 30,000. This differs substantially from the relatively low Mg/Ni ratio observed in kimberlite waste rock samples (Table 1). The high ratio in seepage from kimberlite is caused by the relatively high solubility of minerals that contribute magnesium (carbonates and secondary sulphates), low solubility of minerals that contribute nickel (silicates) and the reduced solubility of nickel at pH's above 7.

Seep-081

The kimberlite signature is observed in seepage from kimberlite waste rock but concentrations are rather lower than those from the CKRSA. Seep-081 drains residual kimberlite sand in a Misery kimberlite stockpile. The chemistry reflects a combination of kimberlite weathering, interaction with the tundra, and dilution by waters within the tundra.

The gradual increase in Seep-081 of Mg/Ni from 2002 to 2007 (Figure 4) was caused by a gradual increase in magnesium concentration throughout this period. While the storage area was in use, kimberlite was placed as blocks within it. Kimberlite weathers rapidly causing an increase in surface area of mineral grains. Most of the kimberlite was removed by the end of 2007; however, the kimberlite sand that had developed had a much greater surface area than un-weathered kimberlite. This allowed extensive weathering of magnesium carbonate, and increased magnesium leaching. Since 2007, the Mg/Ni ratio and Mg concentration have levelled off reflecting the small amount of kimberlite remaining.

Seep-357, September 2011
Although the tundra/granite signature dominates at Seep-357, the kimberlite signature is observed in the September 2011 data. Increases in sulphate, magnesium, calcium and Mg/Ni are characteristic of this. This seep was sampled following two days of heavy rain which appears to have resulted in flushing of weathering products from the WRSA.

Biotite Schist Signature
Based on the seepage data, the most distinctive features of biotite schist leaching appear to be:

- Elevated Ni, Zn, Co, Cu and Cd from sulphide oxidation;
- Elevated F from leaching of biotite;
- Low Mg/Ni ratio.

These characteristics are indicated by the chemistry of Seep-052 but also from other independent sources. Humidity cell testing of Misery schist prior to mining indicated that this rock type produced acid under laboratory conditions as a result of sulphide oxidation (Norecol, Dames and Moore 1997). This produced elevated metals including up to 1.2 mg/L Ni, 1.1 mg/L Zn, 0.34 mg/L Co, 0.76 mg/L Cu, 0.007 mg/L Cd, and SO_4 concentrations of up to 170 mg/L. These are all similar to maximum concentrations observed in Seep-052. In addition, synchrotron-based micro-XRF and micro-XRD work conducted on biotite schist in nearby Diavik test waste rock piles showed alteration of sulphide grains, including pyrrhotite as a source of Ni and Co, sphalerite as a source of Zn and Cd and chalcopyrite as a source of Cu (Hannam et al. 2011).

Seep-052
Seep-052 has the poorest water quality of the various seeps at Misery. The seepage drains to a mine water containment area and is not released to the environment until water effluent quality requirements are met.

Seepage chemistry at Seep-052 strongly reflects the history of waste rock disposal directly upstream. Stripping for the Misery pit began in August 2000. In May/early June 2001, major ion concentrations were low (SO_4, Mg, Ca, K and Na all at 0.5 to 2 mg/L). These all showed maxima during the summer of 2001 to greater than 10 mg/L. Fe and Al also showed maxima at the same time, along with Sr, Ba, Mn and As. Coincident maxima of all these elements is thought to represent rapid weathering of freshly exposed silicate and carbonate mineral surfaces in biotite schist and kimberlite, which were placed together in the WRSA during the previous winter. This effect immediately followed freshet in 2001 but was short-lived, as concentrations declined later that summer.

During 2002 and 2003 concentrations of Fe and Al dropped to 0.1 mg/L or less, as is typical with seeps that do not interact with the tundra. At the same time, rapid increases in SO_4, Ca, Mg, were observed reflecting kimberlite weathering and leaching. The kimberlite was removed from the WRSA during the winter of 2003/2004 due to the reduction in water quality. Concentrations of Mg and Ca have gradually declined from their peak of around 130 mg/L in 2003 to 15 mg/L in September 2011. This slow decline is thought to result from rapid kimberlite weathering in 2001 to 2003 that generated fine-grained residual kimberlite that was impossible to completely remove once it occurred amongst blocks of biotite schist. Magnesium and Ca are gradually being leached out of this material.

Weathering of sulphide phases in biotite schist is indicated by the increase of several parameters beginning in 2002 and peaking in 2005 to 2006. These include Ni, Zn, Co, Cu and Cd. In addition to leaching of sulphides, silicates in the schist are also thought to be leaching but to a lesser extent. Potassium has not declined since 2005 the way that other major ions have. This correlates with fluoride which is enriched in Seep-052 compared to other seeps. These are thought to be leaching out of biotite. Flouride substitutes for hydroxyl in the crystal lattice of biotite (Latourrette et al. 1995).

Aluminum has not followed this trend, but rather, peaked in 2005-2006 at the same time as Ni, Co, Cu, Zn and Cd. Al has low solubility at neutral pH but greater solubility at depressed pH. Although the pH of Seep-052 has remained neutral, it is thought that sulphide oxidation within biotite schist locally produced acidity within the WRSA (as it did in humidity cell tests, down to pH 3.6; Norecol Dames and Moore 1997), contributing to increased Al solubility. Decreasing concentrations of Ni, Zn, Co and Cd since 2006 may indicate that rates of sulphide oxidation in biotite schist have peaked and are in decline.

Mg/Ni ratio in Seep-052 evolved to a high of 5750 reflecting a dominance of kimberlite leaching, and then to a low of 140 reflecting the peak of biotite schist leaching (Figure 4 and 5f). Mg/Ni ratio has since increased slightly as nickel leaching from sulphides appears to have declined.

CONCLUSIONS

Long term seepage monitoring of WRSAs is important for understanding metal leaching at the site and the interaction of different waste rock types. Detailed interpretation of the dissolved metal concentrations from EKATI seepage has allowed a number of water sources to be recognized, including:

- A tundra/granite signature from interaction with the mineral component of granite-derived soils or low level leaching of silicates in granite waste rock;
- A kimberlite signature which can develop rapidly, produced primarily by leaching of magnesium and calcium carbonates, and secondary sulphates, accompanied by a more subtle signature of silicate weathering;
- A biotite schist signature generated initially by oxidation of sulphides, which can take up to five years to fully develop before declining steadily. This is followed by a signature of silicate weathering which takes much longer to develop and is likely still in the early stages of development in the Misery WRSA.

This study shows that metal leaching in a predominantly neutral pH environment is a significant process even under cold arid conditions. Detailed monitoring data can however be used to understand seepage sources in the context of understanding rock mineralogy. At EKATI, seepage monitoring has been used to inform adaptive management practises such as relocation of waste rock and construction of rock berms to limit seepage and encourage freezing. The data are also used for WRSA expansion design.

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