# Evaluation of Neutral pH Chemical Leaching Properties of Waste Rock at the Meliadine Gold Project

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## Abstract
The Meliadine Gold project is located about 25 km northwest of the community of Rankin Inlet in Nunavut. The site is located in an arid arctic climate zone. Waste rock management planning is underway which considers the neutral pH metal leaching properties of the material. Small scale laboratory tests on waste rock suggest that arsenic will be released to various degrees, but there is minimal evidence of arsenic release to contact water from an on site rock pad consisting of this waste rock. An on-going scale up study program consisting of small and large scale laboratory weathering tests, mineralogical investigations, large scale field weathering tests and site water quality investigations are underway to determine sources of labile arsenic, actual site-specific arsenic release rates and potential effects to the receiving environment. These results will be used to finalize the mine rock management and monitoring plans.

## 1.0 Introduction
Agnico-Eagle Mines Ltd. (AEM) is currently studying the feasibility of constructing and operating a gold mine known as the Meliadine gold project (the Project) located approximately 25 km north of Rankin Inlet in Nunavut. The property comprises several gold deposits occurring as low-sulphide, arsenic-rich gold-quartz veins hosted in volcanic flows and sediments of the Archean-age Rankin Inlet Greenstone Belt.

Geo-environmental characterization of waste rock is ongoing to define and quantify potential releases of arsenic from these materials under site conditions; arsenic being the chemical element of interest at the site. The rock has low concentrations of all other common sulphide metals (such as copper, lead, zinc, cadminum, chromium) and the concentration of these elements in site waters and mine waste leach tests is well below MMER. Particular emphasis was placed on evaluating the bulk weathering characteristics and of arsenic-bearing waste rock to better understand the arsenic release rates and potential effects of exposure of this waste in a bulk rock storage facility (RSF). The study results are being used to develop mine waste rock and water management plans that will minimize negative effects to the receiving environment.

This article presents the study methods and results of the geochemical characterization of greywacke waste rock from the largest gold deposit, the Tiriganiaq deposit. The test methods included standard static and kinetic tests and scaled-up, more site-specific laboratory columns and field weathering tests designed to determine the probable site-specific arsenic release rates. These test results are compared to site water quality data collected from waters in contact with this waste rock generated from earlier advanced exploration mining activities in the Tiriganiaq deposit.

## 2.0 Mine Site and Environment
The Meliadine Project is located on Inuit-owned land, approximately 25 km north of the community of Rankin Inlet (Figure 1).

Figure 1. Meliadine Project Location Map

The Meliadine property comprises several gold deposits hosted in low-sulphide, arsenic-rich gold-quartz veins in volcanic flows and sediments of the Archean-age Rankin Inlet Greenstone Belt (Pincock Allan&Holt, 2008). Six deposits are targeted for development at this time, including, from west to east: Wolf, Tiriganiaq, Pump, Wesmeg, F Zone and the Discovery deposit, which is located approximately 16 km southeast of the Tiriganiaq and 18 km north east of Rankin Inlet. Figure 2 shows the site layout. Mining facilities would be located near the Tiriganiaq open pit. The current mining plan anticipates that the deposits would be mined concurrently through a combination of open pit and underground mining techniques at a total maximum average mill feed of 8500 tonnes per day over an estimated 13-year mine life.

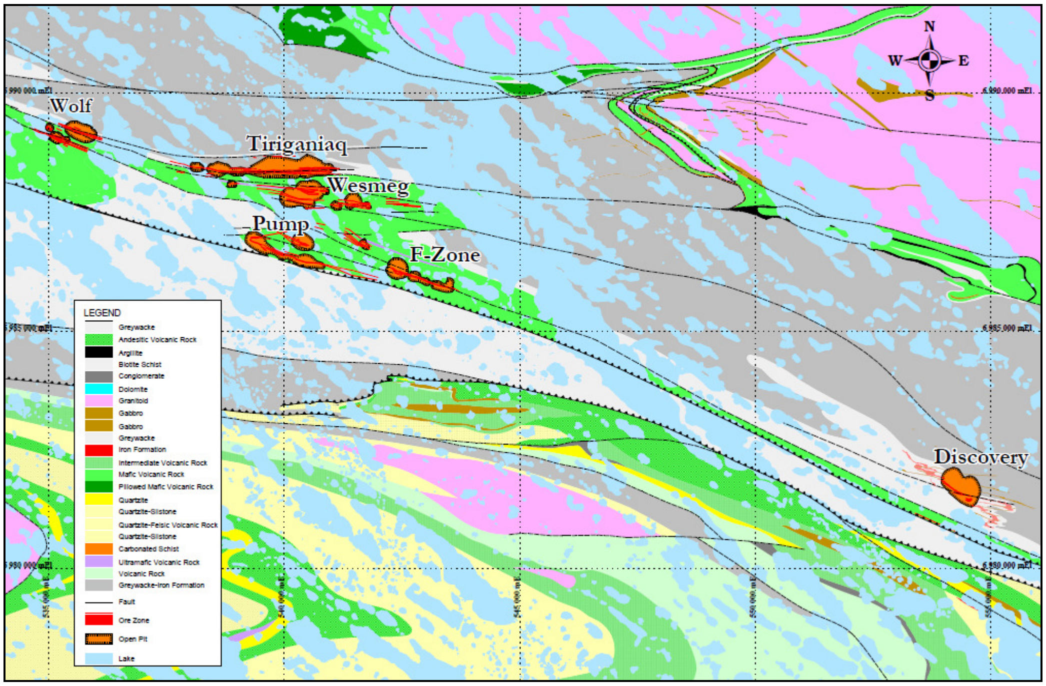


Figure 2. Meliadine Ore deposits

**2.1 Existing waste rock facilities**

Tiriganiaq greywacke rock was extracted in 2008 to build an access ramp for advanced underground exploration and bulk ore sampling of the Tiriganiaq deposit. In 2008, this waste rock was used to form two flat surface pads and an access road between the camp and the portal to the underground. This rock has been exposed to ambient conditions for three years and the edge of the pads is regularly flooded by overland flows accumulating in a low area containing two ponds called the “Primary Containment Pond” and “Sump”. Water quality monitoring is a condition of the exploration water license and these ponds serve to monitor contact water quality as required by Nunavut regulators. The goal of the monitoring is to detect effects to water quality from mining activities, exposed Tiriganiaq waste rock, and crushed ore piles stored on the Operations Pad which contain substantially more arsenic than waste rock. Figure 3 shows the layout of the pads, the Sump and the Primary Containment Pond location. These pads are analogous to the future waste rock storage facility and the Containment Pond and Sump water is anticipated to reflect greywacke waste rock contact water quality.

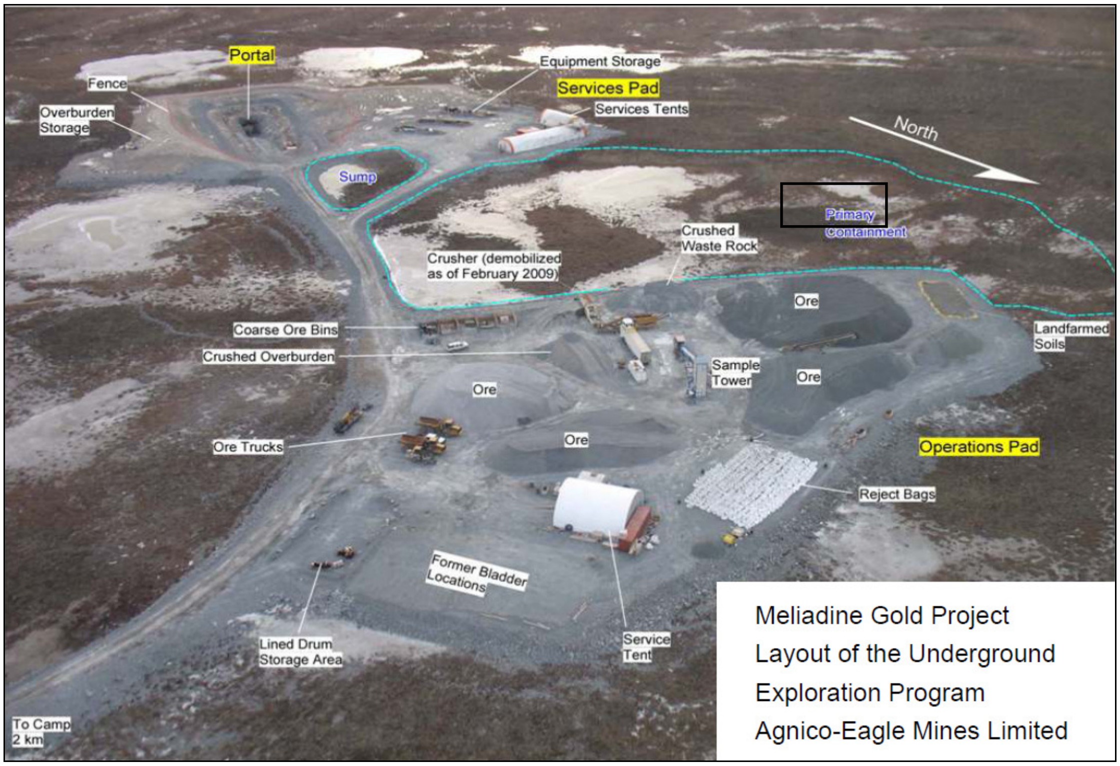


Figure 3. Layout of waste rock pads and the Primary Containment Pond

**2.2 Site climate**

The site is located in an arid arctic environment. It experiences extreme arctic winter conditions, with an annual average temperature of -10 degrees Celsius ($^{o}$C). The monthly mean temperature ranges from -31$^{o}$C in January to +11$^{o}$C in July, with above-freezing averages for only 4 months of the year, from June to September. The site is underlain by thick and continuous permafrost, except under lakes where taliks[1] can exist. The site is indeed arid, with an annual average precipitation of 412 mm/year. The precipitation occurs almost equally as snow and rainfall. Mean annual evaporation for small lakes in the Project area is estimated to be 323 mm between June and September. The mean annual loss of snowpack to sublimation and snow redistribution is estimated to vary between 46% and 52% of the total precipitation for the winter period and occurs between October and May. Experience at the nearby Meadowbank project suggests that in this climate, waste rock piles may not release infiltrated water for a number of years, but that if a water body contacts the rock pile, leaching of waste rock could negatively affect water quality over a short time frame (Robert and Bertrand, 2012). A water collection system will be constructed around the rock piles and tailings storage facility and water quality will be monitored during operation and at closure. A water treatment facility is planned.

**2.3 Mine waste and water management challenges**

The mining lease covers a relatively small area, of which a large proportion is covered by shallow lakes and ponds. Some of the deposits are located under lakes and ponds that will require dewatering before mining. Similarly, land on which to store mine wastes is scarce. As a result, water management is a key aspect of this project. The water management strategy focuses on minimizing water use and disruptions to existing water bodies, maximizing water recycling and controlling the quality of water that will ultimately discharge into Meliadine Lake which is an important resource to the local population. To this end, quantification of the potential chemical releases from waste rock is an important input to water management planning, facility design, mine operation and ultimately, project feasibility.

[1] Unfrozen ground

## 3.0 Arsenic in the Project Area

The Geological Survey of Canada gathered information on the composition of till from the Meliadine Trend (McMartin, 2000) and have found that background arsenic levels are anomalously high on a regional level in soil, and are very locally elevated in surface water samples collected near the deposits (Figure 4).

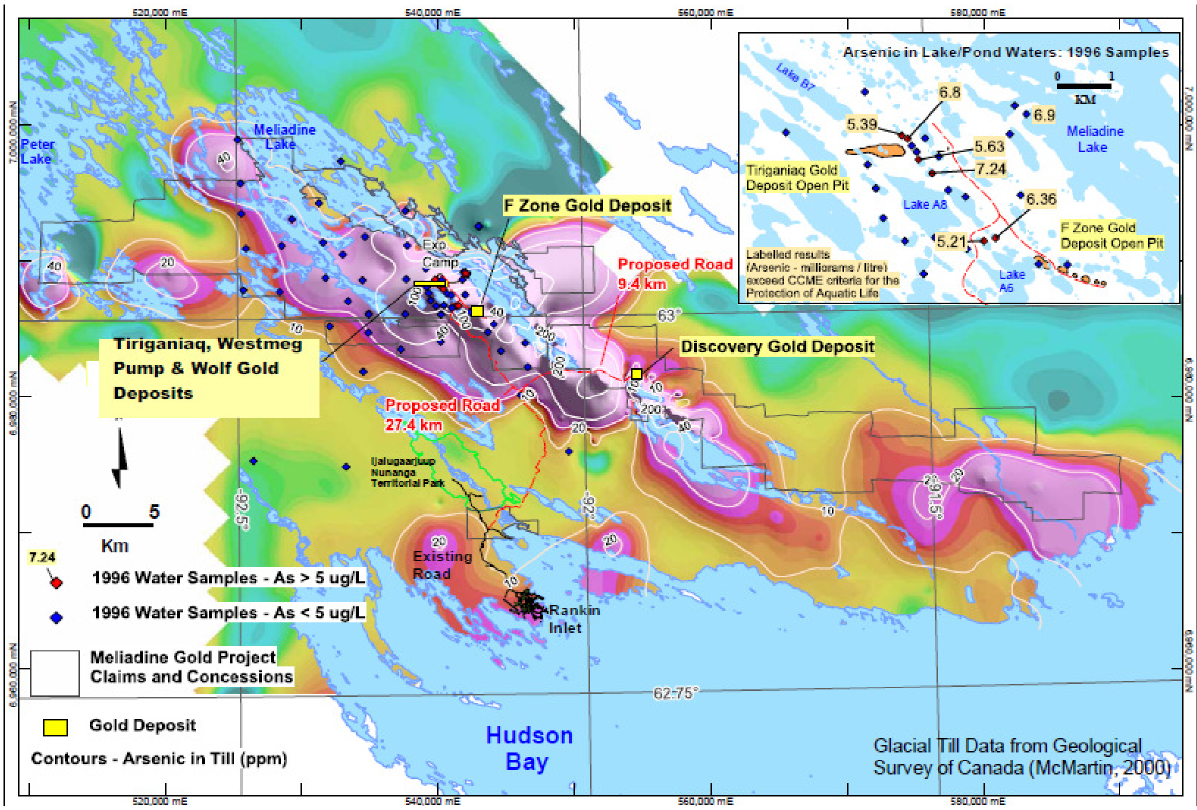

Figure 4. Arsenic concentration in till and surface water

The arsenic concentration in surficial till reflects the presence of arsenic enrichment in the underlying basement rocks associated with gold mineralization. Soil samples analyzed as part of this study confirm the findings of McMartin (2000): 33 samples of soils collected near the deposits show arsenic concentrations ranges from 1.0 to 10,000 mg/kg and average 30 mg/kg and a median of X mg/kg.

The host rocks of the Meliadine deposit that will report to waste upon mining are enriched in arsenic. The highest concentrations are present within the ore zones and in the host rock proximal to these zones. Arsenic concentrations tend to decrease slightly with distance from the ore zone. Of all waste rock types, greywacke waste rock in the Tiriganiaq deposit is the most voluminous waste rock unit. Based on the analysis of 194 samples of core, this rock unit contains concentrations of arsenic that range from 6 mg/kg to 2200 mg/kg near the ore zone, with an average concentration of 158 mg/kg and a median of 51 mg/kg. Figure 5 shows a histogram of arsenic content of Tiriganiaq greywacke waste rock.

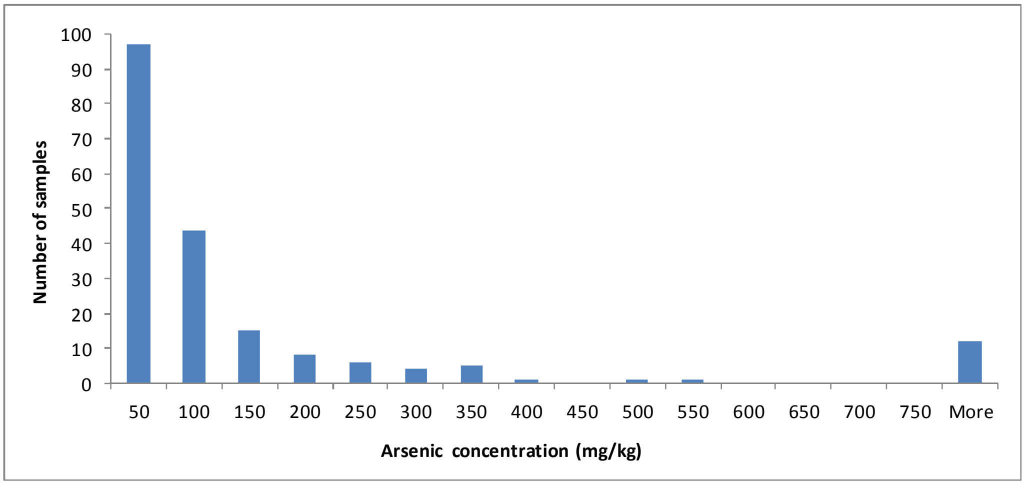


Figure 5. Arsenic content of Tiriganiaq greywacke waste rock

The current mine plan indicates that Tiriganiaq greywacke rock will make up approximately 81% of Tiriganiaq waste rock and approximately 30% of the total waste rock generated by the project. It is the first rock to be extracted during mine development and if geochemically suitable, would be used as construction rock for the mine facilities. This rock is the focus of this article.

## 4.0 Geochemical Characterization of Waste Rock and Contact Water

### 4.1 Sample collection and test methods

A total of 194 samples of waste rock were collected from exploration drill core at locations meant to capture spatial and compositional variability of Tiriganiaq greywacke rock that will report to waste. In addition to these, 12 composite samples of the run-of-mine crushed rock were collected from the Operations Pad by test pitting with a mechanical shovel to 1 to 2 meters depth. Samples were subjected to the following suite of standard geochemical tests at a commercial laboratory:

- Mineralogical composition on select waste rock samples.
- Chemical composition through whole rock and trace element chemistry (aqua regia acid digest and ICP-MS scan).
- ARD potential through acid base accounting (ABA) by the Modified Sobek method (MEND, 2009).
- Net acid generation tests on select waste rock samples (Amira 2002);
- Short-term, readily leachable metals using the shake flask extraction method (SFE; based on ASTM D3987).
- Humidity cell tests (HCTs) on a subset of seven samples of core (based on ASTM D5744) selected to represent median to upper quartile solid-phase arsenic concentration based on the results of static testing. Of these, three have reached 20 weeks of testing and are included in this study.

Larger scale laboratory leaching columns and field cell tests were also initiated, and are on-going, on bulk samples of Tiriganiaq greywacke waste rock to evaluate the effects of scale and site climate on arsenic release rates. The volume of leaching water was designed to be the minimum quantity of water that would yield a sufficient volume of leachate to complete the analytical requirements. This is based on the expectations that the rock piles on site will experience minimal water infiltration given the low annual average precipitation and high evaporation and sublimation rate on site. The bulk sample kinetic tests are described hereafter.

#### *4.1.1 Large scale laboratory leaching columns*

Three large scale laboratory leaching column tests were assembled using composite samples of Tiriganiaq greywacke waste rock from core samples of the static testing program. An equal weight of each sample subjected to static testing was retained (crushed to the same <9.5 mm diameter as the HCTs), and thoroughly blended prior to filling each of the following leaching columns:

- Greywacke open pit East side: All samples from the east side of the deposit within the outline of the proposed open pit (49 samples of 2 kg each; 98 kg total column weight).
- Greywacke open pit West side: All samples from the west side of the deposit within the outline of the proposed open pit (21 samples of 2.3 kg each; 48.3 kg total column weight).
- Greywacke underground combined: All samples from the underground portion of the proposed mine (40 samples of 1.25 kg each; 50 kg total column weight).

The leaching apparatus consists of specially built PVC columns (cylinders) of 91 cm height by 35.5 cm and 25 cm diameter (for 100kg and 50 kg sample charges respectively). They are fitted with a valve at the bottom to release leachate. They are trickle leached (slow rain-like precipitation of water at the top) on a weekly basis with laboratory grade de-ionized water at a 10:1 solid to liquid ratio (the 50 kg column is leached with 5 litres of water, the 98 kg column is leached with 9.8 litres of water). Water is collected at the end of the 7$^{th}$ day, filtered and analysed. Unlike the standard HCT, the leaching columns are not subjected to 3 days of dry air circulation and 3 days of humid air circulation between weekly leaching cycles.

#### *4.1.2 Field cell tests*

Two duplicate field cells were constructed using a composite of run-of-mine waste rock material collected from 12 test pits completed in the operations pad. A composite sample was collected from each test pit for static testing and 50 kg of material was collected from each test pit as charge material for the field cells, resulting in 300 kg of charge material per field cell. This material has coarser particles (up to about 20cm) than the charge material used in laboratory tests but has a similarly high proportion of fines. Cells consist of 55-gallon plastic drums that are open to the atmosphere and are fitted with a hose at the bottom that drains to a closed container. This allows precipitation to flow freely through the charge material and drain to the container. A picture of the field cell set up is shown on Figure 6. The other two cells contain different rock material that is not discussed in this paper.

Figure 6. Field cell test design.

Since their installation during the summer of 2011, precipitation has been too scarce to collect adequate volumes of water for analysis, consequently, the cells were actively leached on a monthly basis with nearby lake water (containing very low dissolved solids; < 20 µS/cm conductivity, as is typical of arctic lakes in headwaters) at a 60:1 solid to liquid ratio (5 litres of water for 300 kg of charge material). This represents approximately 47 mm of rain, or an average summer month's precipitation fully infiltrated into the rock. The lake water contains no detectable arsenic and the small concentration of constituents present in the water was substracted from the field cell leachate chemistry to yield a field cell specific water quality. Water collecting in the receptacles was filtered and placed in laboratory-supplied bottles with preservative for shipping to a commercial analytical laboratory.

## 5.0 Results

As documented in the exploration database, the rock contains low concentrations of metals commonly present in sulphides (such as copper, lead, zinc, cadminum, chromium) and the concentration of these elements in site waters and mine waste leach tests is well below MMER. Thus, results focus on arsenic. The rock contains arsenopyrite (FeAsS) and arsenic-rich pyrite ($FeS_2$), documented in the exploration database, mainly in ore but sometimes detected in trace quantities in a few samples of greywacke waste rock. X-ray diffraction and the mine site mineralogical database corroborate to show that the greywacke has little sulphide minerals. Acid-base accounting agrees with mineralogical data, showing low sulphide sulphur content (average of 0.09% sulphide) and ample carbonate buffering capacity; where the carbonate content-derived NP matches the bulk neutralization potential determined by the MEND 2009 NP determination (previously known as the modified Sobek Method). Mineralogical observation shows the presence of calcite, dolomite but also ankerite ($Ca(Fe, Mg, Mn)(CO_3)_2$). The rock is non acid generating (net potential ratio (NPR) values range between 4 and 430, with an average of 36 and a median of 19, compared to a typical cut off of 2 for potentially acid generating material). Oxidation of such small quantity of sulphide is not expected to substantially increase the metal load to receiving waters. Conversely, should arsenic be associated with carbonate or other soluble minerals as impurities or trace constituents of these minerals, arsenic could be released faster and at higher rates than expected from the oxidation or dissolution of arsenopyrite or pyrite. Further mineralogical testing is on-going with more detailed investigation tools to define the source of arsenic for samples where no arsenic mineral phases were observed by X-ray diffraction but that still yield arsenic in leachate. These include Qemscan and Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy to target individual mineral phases as well as sequential leachate extractions to identify arsenic-hosting mineral phases.

As indicated previously, the average arsenic content of Tiriganiaq greywacke waste rock is 154 mg/kg, but ranges from 6 to 2200 mg/kg in the ore zones. The waste rock releases arsenic under water leach tests (SFE), mostly as As 3+ as determined from arsenic speciation analysis of the leachates. Arsenic leachability does not correlate with solid phase arsenic content ($R^2<0.3$), thus arsenic is likely associated with various mineral phases that have differing solubility. Table 1 presents a summary of analytical data relevant to this study. Humidity Cell Tests and leaching column kinetic test data are after 20 cycles of testing; field cell leachate data are after 3 cycles of testing.

Table 1. Solid Phase and Leachate Arsenic Content of Waste Rock

| Rock Sample type | Test | Number of tests | Solid Phase Arsenic (mg/kg) | | Leachate Arsenic (ug/L) | | | Arsenic load |
|---|---|---|---|---|---|---|---|---|
| | | | range | average | SFE average | Kinetic Test range | Kinetic Test Average | average (mg/kg/cycle) |
| Core | Static SFE | 171 | 6.0 - 2200 | 154 | 52 | - | - | 220 |
| | Humidity Cell | 7* | 130 - 1300 | 368 | 60 | 1 - 18 | 7.0 | 8 |
| | Leaching Column | 3 | 121 - 310 | 221 | 61 | 10 – 140 | 68 | 7 |
| PAD Run-of-mine rock | Static SFE | 13 | 32 - 630 | 147 | 53 | - | - | 220 |
| | Field Cell | 2 | 32 - 630 | 147 | - | 6.5 – 7.0 | 7.0 | 0.1 |

Notes:
SFE - shake flask extraction static leach test
*static test results from 7 samples, kinetic test results on 3 samples that reached cycle 20.

HCTs and leaching columns consistently yielded neutral pH leachates (pH range between 7.1 and 8.8 throughout testing). Arsenic concentrations reached a relatively steady leaching rate early in the test (generally after less than 10 cycles); the higher concentrations ranges reflect the peaks of the initial flushing events. The field cell leachate concentrations and loads may represent a conservatively high estimate of arsenic loading if the 3 cycles monitored to date represent first flush conditions. Figure 7 shows arsenic concentration in time kinetic testing. Concentrations are shown in mg/L.

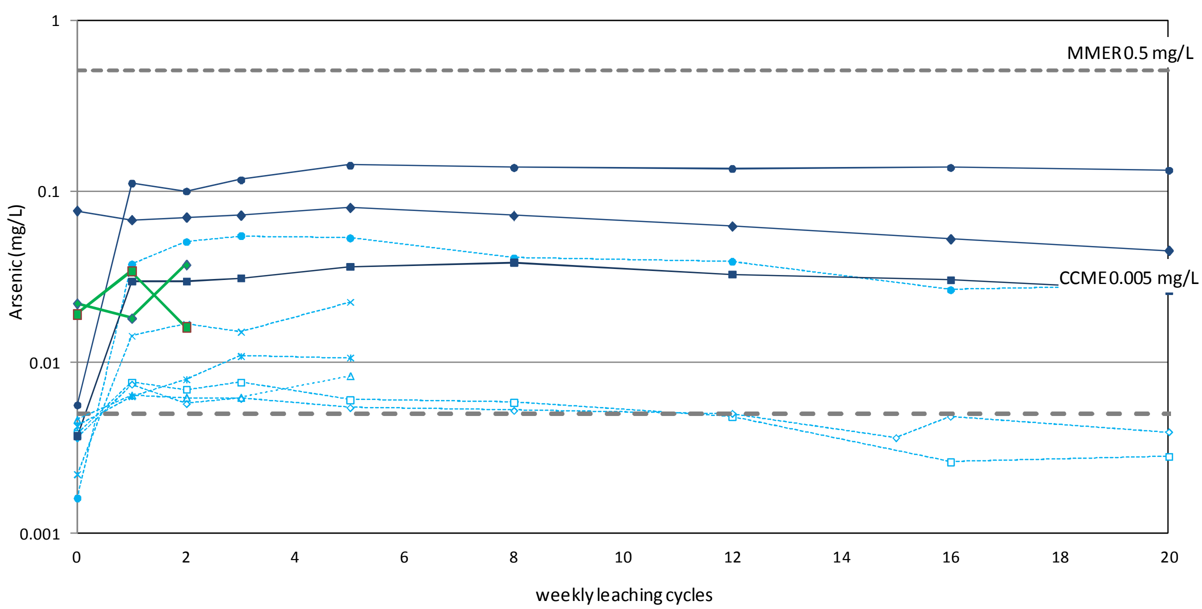


Figure 7. Kinetic test leachate arsenic concentrations in time.
HCT in light blue, large leaching columns in navy and Field cells in green.

The results of standard static leaching tests are an order of magnitude higher than the Primary Containment Pond water quality which is in close contact with the waste rock pile. The range of arsenic concentrations measured at P1 and in downstream shallow lakes and ponds is presented in Table 2.

Table 2. Total Arsenic Concentration Ranges at Surface Water Monitoring Stations (ug/L)

| | Primary Containment (P1) | Lake A54 downstream of P1 | Lake A38 downstream of A54 | Lake A8 downstream of A38 |
|---|---|---|---|---|
| April 1997 - October 2007, before underground development | | | | |
| Number of analyses | 0 | 4 | 3 | 8 |
| minimum | n/a | 3 | 4 | 2 |
| maximum | n/a | 4 | 5 | 4 |
| median | n/a | 4 | 5 | 2 |
| average | n/a | 4 | 5 | 2 |
| May 2008 - July 2010, after underground development | | | | |
| Number of analyses | 8 | 10 | 6 | 10 |
| minimum | 2 | 1 | 3 | 1 |
| maximum | 29 | 4 | 6 | 3 |
| median | 9 | 3 | 4 | 2 |
| average | 12 | 3 | 4 | 2 |

n/a - sampling location does not exist

Table 2 shows that the bulk leaching tests are more in line with site water quality monitoring data. Shallow piezometers installed in 2011 at the toe of the waste rock pile within the active thaw depth (at 1.5 meters depth) are expected to provide further information on water quality seeping from the pile.

Figure 8 shows that the arsenic load released from the rock depends on the amount of water contacting the rock and varies proportionately with the solid to liquid ratio of the test.

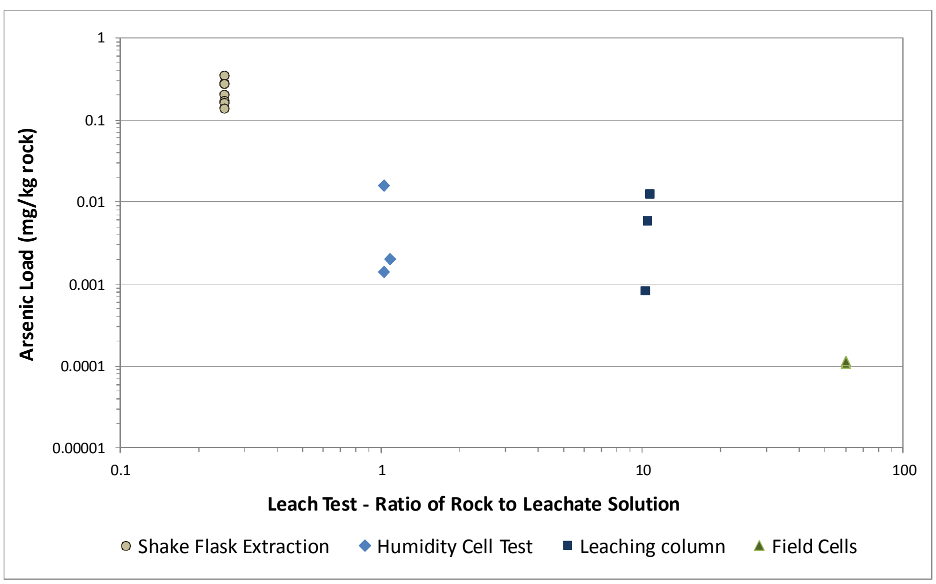


Figure 8. Arsenic load released at various leaching test conditions

## 6.0 Conclusion

For sites located in a dry climate and where chemical releases from low sulphide mine wastes are dictated by mineral dissolution more than sulphide oxidation and acidification, the effects of mine waste exposure on receiving water quality will be a function of the interaction of water and waste rock. Low water infiltration and flushing correspond to low chemical loading rates. This is substantially different to high sulphide waste rock where oxidation can proceed with little moisture and the oxidation products (metal salts, acid) can be released at the next rain event at high concentrations in small volumes of water.

For the case studied, the standard short-term water leaching test used (SFE) is ill suited to evaluate the likely chemical release rates from the waste rock. Site-specific kinetic leaching test conditions and detailed mineralogical analysis are better methods to identify the source and occurrence of the labile elements of interest, their weathering behavior and their probable release rates upon exposure to site conditions.


## Acknowledgement

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## References


American Society for Testing and Materials (2001). ASTMD5744-95. Standard Test Method for Accelerated Weathering of Solid Materials Using a Modified Humidity Cell. ASTM Technical Subcommittee D34-01-04 on Waste Leaching Techniques. Re-approved 2001.

American Society for Testing and Materials (2006). ASTM D3987-06. Standard Test Method for Shake Extraction of Solid Waste with Water. ASTM Technical Subcommittee D34-01-04 on Waste Leaching Techniques.

AMIRA (Amira International Ltd.) (2002). ARD Test Handbook – Prediction and Kinetic Control of Acid Mine Drainage. Environmental Geochemistry International Pty Ltd. and Ian Wark Institute, University of South Australia.

McMartin, I. (2000). Distribution of Au and As in till from the Meliadine Trend, Nunavut; Cordilleran Exploration Roundup 2000, Vancouver, B.C., January 2000

MEND (2009). Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials. MEND Report 1.20.1. Mining Environment Neutral Drainage Program, Natural Resources Canada. December 2009.

Pincock, Allen and Holt (2008). Technical Report for the Meliadine East Project (NI 43-101 report). Prepared for Meliadine Resources Ltd. On Behalf of the Meliadine East Joint Venture. April 18, 2008

Robert, S. and V. Bertrand, (2012). The Meadowbank Gold Mine – Reclamation Planning in an Arctic Environment. In: 9th International Conference on Acid Rock Drainage (ICARD), May 2012. Ottawa, Ontario.


## Acronyms

| | |
|---|---|
| ABA | Acid Base Accounting |
| AEM | Agnico-Eagle Mines Ltd. |
| ARD | Acid Rock Drainage |
| As | Arsenic |
| ASTM | American Society for Testing and Materials |
| FeAsS | Idealized mineral formula for arsenopyrite |
| $FeS_2$ | Idealized mineral formula for pyrite |
| HCT | Humidity Cell Test |
| ICP-MS | Inductively Coupled Plasma - Mass Spectrometry |

| | |
|---|---|
| kg | kilogram |
| L | litre |
| mm | millimetre |
| mg | milligram |
| NPR | Net Potential Ratio NPR = neutralization potential/acid potential |
| RSF | Rock storage facility |
| SFE | Shake Flask Extraction Test |