SCALE UP EFFECTS ON MASS LOADING RATES IN AN ARID ARCTIC ENVIRONMENT[1]

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Abstract. The Meadowbank Gold Project of Cumberland Resources Limited is located 70 km north of Baker Lake in the arid, arctic environment of Nunavut Territory, Canada. With a site annual average temperature of -11°C, and 310 mm/year precipitation, the extrapolation of constituent loading rates from laboratory tests is particularly precarious. Three different scales of kinetic leaching tests were performed on waste rock samples: 1-kg and 100-kg laboratory leaching cells and 250-kg field cell tests.

Field tests yielded considerably slower rates of buffering capacity depletion and sulfide oxidation than laboratory-derived rates, although the differences were not consistent between the various test scales.

Additional Key Words: kinetic test, buffering, sulfide oxidation

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Introduction

A mine site material and tailings characterization program was developed by Golder Associates Ltd. (Golder) for the proposed Meadowbank Gold Mine located 70 km north of Baker Lake in Nunavut, Canada (Fig. 1). The results of this program were used to develop water quality predictions for each mine component (Golder, 2005a, 2005b, and 2005 c). As part of the characterization program, static and kinetic tests were conducted on the three principal rock types that will be disturbed by mining. Kinetic tests have been conducted on all rock types at different scales to characterize the development of ARD, if any, and in-situ chemical leaching rates. One of these rock types, altered volcano-clastic tuffs and agglomerates referred to as intermediate volcanic (IV) rock, has a variable acid rock drainage (ARD) potential, with no discernible field marker to segregate potentially acid generating (PAG) from non-PAG rock. Emphasis was placed on evaluating the bulk weathering characteristics of this rock type to better understand the potential effects of disposing this waste in a bulk rock storage facility (RSF). This paper presents the characteristics of each rock type, kinetic test methods, a summary of the study results and a discussion on trends observed for the different scales of testing.

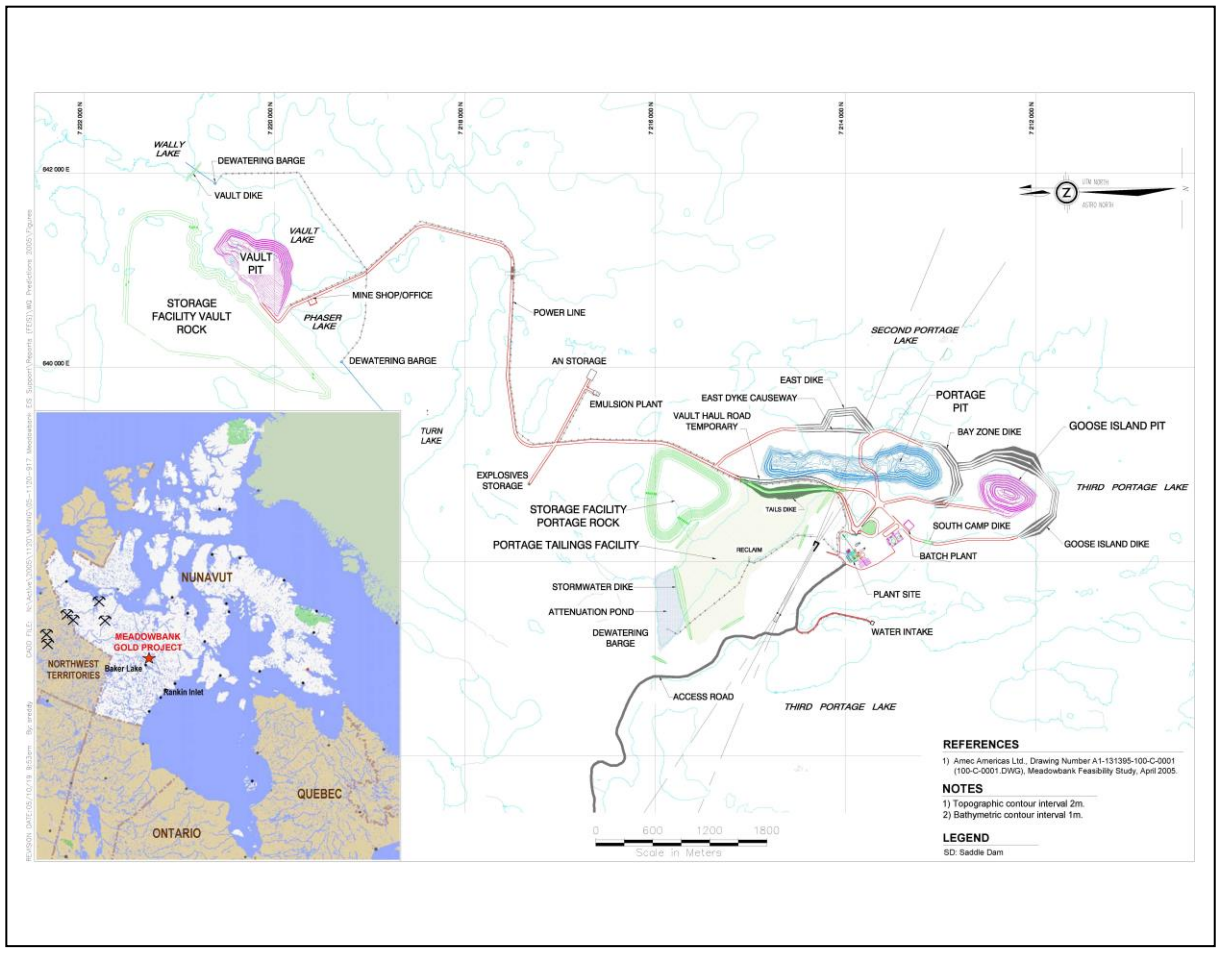


Figure 1. Site location.

Background Information

Site Climate

The average annual temperature at site is -11.8 ºC, with four of 12 months having a daily average temperature above 0ºC (June to September). Average annual precipitation is 310 mm/year, with 157 mm as rainfall, the balance as snow but with sublimation removing approximately 40% of the winter snowfall.

Waste Rock Management Plan

During mine life, it is expected that a total of 180 million metric tonnes of rock will be generated from three open pits: Goose Island and Portages pits in the southern portion of the site and Vault pit, located five kilometers to the north of the Portage pits (Fig. 1). Pit waste rock will be deposited in two RSFs: the Portage RSF containing waste rock from the Portages and Goose Island open pits, and a Vault RSF containing only Vault pit waste rock.

Geology and Geochemical Characteristics

The three major rock types to be disturbed by mining include: felsic to intermediate volcanic rock (IV) consisting mainly of sericitized and chloritized volcanoclastic tuffs and agglomerates; oxide-facies banded iron formation (IF); and amphibolitic to komatiitic mafic volcanic to ultramafic rock (UM). The Goose and Portages deposits intersect IV, IF and UM rock and as such, the Portage RSF will contain a mixture of IV, IF and UM rock. The bulk of the rock in the Portage RSF has the potential to generate ARD and consequently, will be covered with a layer of run-of-mine acid-buffering UM rock that is expected to host the active thaw zone (the core of both RSFs is predicted to become permanently frozen). The Vault deposit is hosted almost exclusively in IV rock and this rock type will be the main constituent of the Vault RSF. Although some samples from this rock are PAG, the bulk of Vault IV rock is acid-buffering and, consequently, the Vault RSF will not be covered at closure. Compositional characteristics of each rock type are presented in Table 1.

At the Portages and Goose deposits, mineralization in all three rock types is associated with moderate to strong sulfidization and silicification. The main sulfide minerals are pyrrhotite [$Fe_{1-x}S$] and pyrite [FeS_2], traces of chalcopyrite [$CuFeS_2$] and arsenopyrite [FeAsS] are also present. The pyrrhotite content of the ore decreases from south to north. At the Goose Island deposit, pyrrhotite constitutes approximately 50% of the iron sulfides, while at Vault, more than 90% of the iron sulfides occur as pyrite (Golder, 2005a).

Three different scales of kinetic leaching tests were performed on waste rock samples: 1-kg and 100-kg laboratory leaching cells and field cells of 200 to 250 kg. Table 2 provides a summary of the characteristics of each sample subjected to kinetic testing (1-kg samples and the 100-kg composites) as well as the median values for the entire database of static test results for each rock type. Field cell charges consist of core sections selected within and adjacent to intervals sampled for 1-kg and 100-kg static tests. Consequently, the composition of the material in the field cells is represented by the average composition of each lithology, determined from the entire database of static test results.

In general, the bulk of IF waste rock is considered PAG while UM rock is considered non-PAG. UM rock contains the highest median neutralization potential (NP) of all rock types. Goose-Portage and Vault IV lithologies have a slightly more variable ARD potential. However, the bulk characteristics from the two riffle-splits of the 100-kg composite Goose-Portage and Vault IV samples (NPR of 6.0 and 2.9 kg/tonne for each rock type respectively) and the overall

NPR calculated from the entire database of results from 1-kg samples[1] suggest non-PAG designations for IV rock from both areas. The overall NPR of the database (of 2.6 and 2.5 kg/tonne for Goose-Portage and Vault IV rock, respectively) is calculated from the ratio of sum of NP (1338 and 2081 kg/tonne respectively) to the sum of AP (507 and 824 kg/tonne respectively).

Table 1. General characteristics of each rock type

	Vault	**Goose Island and Portage**		
Rock Type	**IV**	**IV**	**IF**	**UM**
Proportion[1]	~100%	28%	35%	35%
Geology	volcanic tuffs, agglomerates (graywacke)	volcanic tuffs, agglomerates (graywacke)	oxide-facies banded iron formation	amphibolite, komateite, mafic to ultramafic
Mineralogy	quartz, muscovite, chlorite, dolomite, calcite, pyrite, some pyrrhotite, minor arsenopyrite, trace chalcopyrite	quartz, muscovite, chlorite, calcite, dolomite, minor siderite, arsenopyrite, pyrrhotite, minor arsenopyrite, trace chalcopyrite	quartz, magnetite, amphibole, chlorite, pyrrhotite, pyrite trace calcite	talc, chlorite, dolomite, some calcite, trace: siderite, pyrite, pyrrhotite, and chalcopyrite
Average Sulphide Content	0.75%	0.26%	1.2%	0.2%
ARD Potential[2]	11% PAG 14% uncertain 75% non-PAG	20% PAG 14% uncertain 66% non-PAG	67% PAG 13% uncertain 20% non-PAG	2% PAG 2% uncertain 96% non-PAG

[1] Excludes other minor rock types not discussed in this paper
[2] ARD Potential according to INAC (1992) guidelines:
PAG : NPR < 1
Uncertain : 1 < NPR < 2
non-PAG : NPR > 2

[1] Entire database of results not shown

Table 2. Summary of ARD characteristics and arsenic and iron content

Rock Type	Sample	Total Sulfur (%)	Sulfate Sulfur (%)	AP[1]	NP[2]	CaNP[3]	NPR[4]	As (ppm)	Fe (%)
				($CaCO_3$ kg / tonne rock)					
Vault Deposit									
IV 1-kg samples	V01-02	3.1	<0.01	97	79	86	0.8	96	5.2
	V23-05	0.1	<0.01	3.4	40	39	11	11	2.4
	Median (n=36)	0.3	<0.01	8	56	63	6.9	17	4.8
IV 100-kg Composite		0.6	<0.01	18	53	59	2.9	690	5.0
IV 258-kg Field Cell[5]		0.8	<0.01	23	58	69	2.5	148	4.7
Goose and Portage Deposits									
IV 1-kg samples	NP40-03	0.9	<0.01	28	4.1	334	0.1	1650	7.1
	G131-01	1.3	<0.01	40	1.9	28	0.1	475	5.0
	TP372-01	0.4	<0.01	13	7.3	5	0.6	102	4.3
	NP140B-02	0.2	<0.01	5.3	99	131	19	10	5.9
	Median (n=71)	0.1	<0.01	3.5	9	8	2.5	4.0	5.1
IV 100-kg Composite		0.2	<0.01	7	40	33	6.0	570	5.0
IV 227-kg Field Cell[5]		0.3	0.01	7.9	22	33	2.8	84	5.3
IF 1-kg samples	G103-03	4.6	0.2	137	2.7	1.7	0.1	6.0	34
	G051-01	0.4	0.1	9.7	3.1	0.8	0.3	12	36
	TP023-01	0.7	0.0	21	7.4	1.7	0.3	36	34
	TP344-03	2.2	0.1	66	3.9	2.5	0.1	71	19
	Median (n=46)	0.8	0.1	27	6.1	5.8	0.2	4.0	28
IF 205-kg Field Cell[5]		1.2	0.06	36	21	28	0.6	131	14
UM 1-kg samples	G108-01	0.1	<0.01	3.1	176	182	56	7	6.5
	NP40-02	<0.01	N/A	<0.3	273	298	>875	89	7.0
	Median (n=54)	0.04	<0.01	1.1	90	103	82	1.0	7.0
UM 243-kg Field Cell[5]		0.20	<0.01	6.3	102	118	16	15	6.6

[1]AP: acid potential using sulfide sulfur (Total S - Sulphate S)

[2]NP: neutralization potential using Modified Sobek Method (Price, 1997).

[3]CaNP: carbonate neutralization potential calculated from Total Inorganic Carbon (Price, 1997)

[4]NPR: net potential ratio (NP/AP); median NPR calculated as the ratio of median NP to median AP

[5]Estimated composition based on average concentration of all static test samples from each deposit
NPR statistics uses "greater than" values as the actual value

Methodology

Sample Selection

1-kg Humidity Test Cells (HCT). Of all the samples analyzed as part of the geochemical program (over 270 samples), a total of 12 samples were selected for kinetic testing: six samples of IV, four samples of IF, and two samples of UM rock (Table 2). Sample selection focused on representing the average and higher concentration ranges for constituents of environmental interest. The samples selected were considered to be the most representative of each lithology based on a statistical evaluation of the static test database for key geochemical characteristics by rock type, principally total S and As content (Golder, 2005b). The average surface area of the 1-kg charge material, calculated from sieve analysis after kinetic test termination, ranges between 5,000 cm^2/kg in stronger IF rock to 15,000 cm^2/kg in softer UM rock, with an average of 9,300 cm^2/kg.

100-kg Composite IV Columns. The charge material included the unused portion of all Vault IV and Goose Island/Portage IV core samples characterized under the static test program, and

consequently, of known chemical characteristics and proportion in each column. Some IF samples (8 wt.%) and UM samples (16 wt.%) were inadvertently included in the Goose-Portage column. A separate aliquot of each composite IV sample was riffle split and subjected to acid-base accounting (ABA) (Table 2). The 100-kg composite sample is representative of the bulk chemical characteristics of Vault and Goose-Portage IV rock, as shown in Table 2 by the similarity in chemical characteristics with the median values from the static test database. The surface area of the charge material was calculated from sieve analysis of the entire charge material after termination of testing. The surface area of the Goose/Portage column is estimated at 480,000 cm^2 and Vault IV at 720,000 cm^2, for an average of 6,000 cm^2/kg of charge material.

Field Cells. Charge material was obtained from drill core samples of waste rock collected from within and adjacent to intervals sampled for 1-kg and 100-kg static tests. As such, the field cell charge material is considered to be similar to, although not exactly the same, as the 100-kg column charge material, and is considered representative of the bulk chemical characteristics of each lithology. The cores (2.6 cm diameter) were broken into segments up to 20 cm long, some of which were split vertically (for ore grade analysis). Fines were also present particularly in fracture zones, more prevalent in UM rock. Prior to charging each cell, the surface area of the charge material was estimated by spreading the charge material on a tarpaulin and grouping together core segments of approximately equal length (+/- 1 to 2 cm). Each group was weighed, with fines (<5 mm) collected and weighed separately. The surface area of each group of samples was calculated considering the average specific gravity of the rock, the mass and average volume of the samples in each group relative to the total mass of the charge material. The total surface area of each group of samples was then added to estimate the total surface area of the charge material. The total surface area of field cell charge material ranges between 110,000 cm^2 for IV rock from the Vault area, to 830,000 cm^2 for the softer UM rock. The average surface area per unit weight of field cell charge material is 3,200 cm^2/kg for UM rock and ranges between 970 cm^2/kg and 550 cm^2/kg for the other charges (IF and both IV rock types).

Kinetic Test Methods

A total of 19 kinetic tests were conducted on samples of pit rock waste. The twelve 1-kg humidity test cells were conducted generally following the ASTM (1996) testing procedure. Each bottom-perforated acrylic cell was loaded with a 1.0 kg charge of minus 6.3mm jaw-crushed rock (core) on top of which was placed a length of coiled tubing punctured with holes. This tubing passed through the lid of the cell and into a feed bottle containing laboratory-grade ultrapure distilled water. Each cell was trickle-leached with 500 mL of distilled water over a twenty-four hour period. Each humidity cell leach cycle was seven days in length, consisting of three days of dry air flow through the cell, followed by three days of humid air flow, and a final trickle-leach day when feed water was allowed to percolate through the sample and drain into a collection vessel for analysis.

Two large-scale (approximately 100 kg) leaching columns were constructed for the purpose of the project (Fig. 2). The columns were made from acrylic clear boxes having a 27 cm by 27 cm base, and a 1.24-metre height. A perforated PVC support plate was positioned approximately 2.5 cm above the base of each cell. The Goose-Portage and Vault IV columns were charged with 96 and 93 kg samples of IV core, respectively. The core samples were crushed using a jaw crusher to minus 6.3 mm. The cells were trickle-leached following the same seven-day leaching procedures as the 1-kg tests but with a smaller volume of water to better approximate expected field conditions. During the initial flush (Cycle 0), 4.5 L of distilled water was trickled over a

twenty-four hour period. After that, 3.0 L of ultrapure water was used to trickle-leach the cells over a twenty-four hour period. The three-day dry air and humid air cycles were conducted in the same manner as for the 1-kg columns.

The five field cells consist of 45-gallon recycled metal drums that were previously cleaned with detergent and water, rinsed and fitted with 0.15-mm low-density polyethylene bags. A threaded plastic nozzle and fitting were placed at the base of each cell to allow water to flow freely out of the cell, to which was attached ½ inch of Tygon tubing with a stopper for leachate collection. The base of the drums was filled with a 10-cm thick layer of washed silica sand #75, topped by two layers of plastic mesh filter. Charge material was added on top of the sand and filter.

Four cells were filled with 200 to 250 kg each of UM, IF, Goose/Portage IV, or Vault IV rock, and a control cell was filled with filter sand only (Fig. 3). The drums were kept open to the atmosphere to allow rainfall and snow melt to flow through the cell. Each drum was placed on a slightly tilted surface to facilitate the flow of leachate out of the cell. The leachate collection system was checked after each rain event and when available, samples were collected from each of the five cells. On occasion, precipitation alone did not generate a sufficient volume of water for analysis of all constituents of interest. On these instances, three litres of water from an adjacent lake (of less than 20 uS/cm conductivity) were used to leach field cells. Lake water was also analyzed when used for leaching. The leachate samples were shipped directly to a commercial laboratory for chemical analysis.

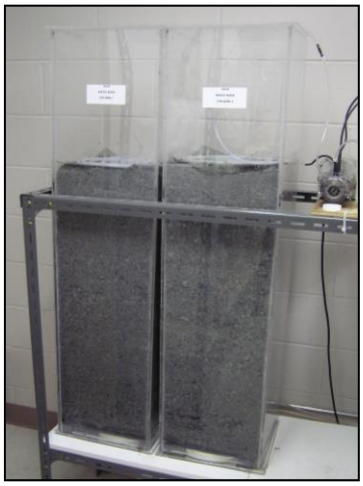


Figure 2. Leaching columns

Figure 3. Field cell tests

The 1-kg cells and 100-kg leaching column charge material were subjected to the same crushing method and have similar surface areas per unit mass. The field cell charge materials have fewer fines and consequently, have a lower surface area per unit mass. The major differences between the 1-kg cells and 100-kg columns conducted for IV rock are: 1) the solid to liquid ratio and consequent flushing rate which is 10 times higher in 1-kg cells; and 2) the composition of the charge material. The 1-kg cells contain samples that represent selected compositional features of each lithology. Individually, these samples do not capture the compositional variance of each lithology, which is why the leaching rates of the 1-kg cells must

be factored and combined to extrapolate to a leaching rate that will describe each lithology. Conversely, the 100-kg columns contain rock of mixed composition such that each cell captures the compositional variance of the IV lithology. A consequence of this discrepancy is that the lithological leaching rates obtained from the 1-kg samples include metal leaching rates from cells that generated ARD and therefore differ considerably from metal leaching rates obtained from 100-kg composite samples that did not generate ARD during testing.

The differences between the field cell charge materials and the 100-kg columns (for IV rock types) are: 1) the differing surface area per unit mass of the charge materials and, 2) test temperature. Differences in charge material composition are considered minor; they include core samples of mixed ARD potentials obtained from similar geographic locations. The flushing rate per cycle is also similar although cycles are farther apart (monthly) in field cells compared to 100-kg columns (weekly).

Table 3 provides a summary of the kinetic test variables. The laboratory tests were conducted until stable[2] leaching rates were obtained; the field tests were on-going in January 2006.

Analyses. Leachates from all kinetic tests were analyzed for total and dissolved metals, major ions, nutrients, alkalinity, specific conductivity and pH. Analyses were conducted at certified commercial laboratories using methods that allow low-level detection limits. Leachate duplicates were taken on 10% of the laboratory samples. The density of duplicate leachate analysis was lower for field cells. Solids analyses were also conducted at commercial laboratories in Vancouver, Canada. Solubility constraints were verified for all kinetic test leachates (final week leachate solutions) using the USGS PHREEQC speciation code (Parkust and Appelo, 1999) to check for solubility constraints.

Table 3. Summary of kinetic test variables.

Charge (Pit Waste Rock)	**Grain Size**	**Leaching Cycles**			**Average Test Temperature**	**Number of Cells**	**Test Duration (weeks)**
		liquid to solid ratio	pore volume per cycle[1]	frequency			
1-kg HCT: all major rock types	<6.3mm crushed core	0.5L : 1kg	3	weekly	21ºC	12	20 to 93
100-kg columns: composite IV rock	<6.3mm crushed core	0.03L : 1kg	0.2	weekly	21ºC	2	57
200-250 kg field cells: all major rock types	2.6-cm diameter core sections	~0.016L : 1kg (variable)	0.1 to 0.3[2]	monthly (June-September)	7.5 ºC [3]	5	August 2003 to present

[1]assuming bulk density of 1.8 to 2 tonnes/m^3;[2] monthly cycle; [3]summer average (June to September)

[2] 5 cycles or a 10-week period where leachate concentrations varied by less than 20%

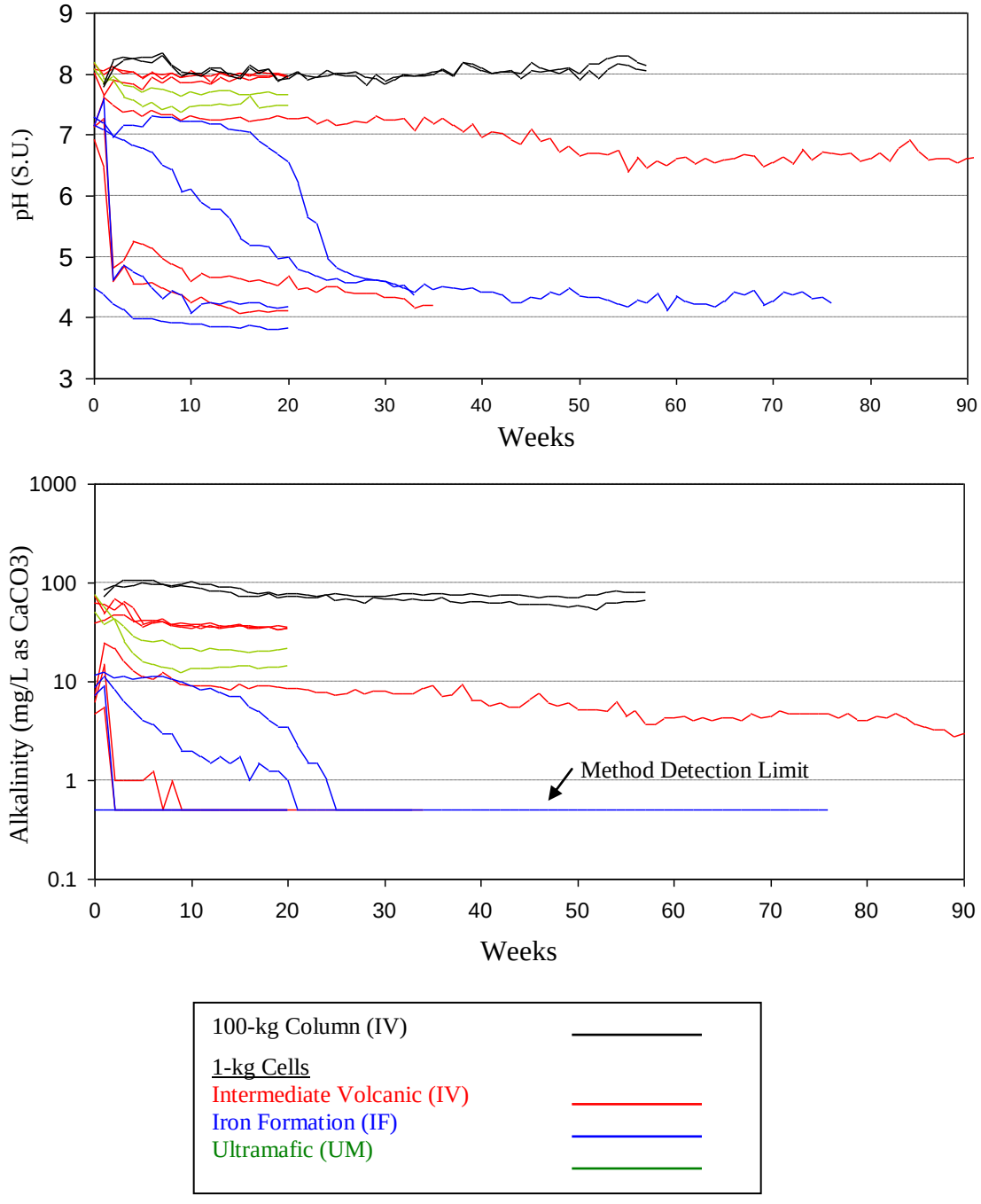
Results

The balance of acid-producing and acid-neutralizing reactions for each rock type is presented graphically as time-series plots of pH and alkalinity for all laboratory cells (Fig. 4) and field cells (Fig. 5). Figure 4 shows that drainage from UM rock samples (green lines) remained neutral throughout testing at both the 1-kg laboratory scale and the field scale, although alkalinity levels from field cells were slightly higher than those from the laboratory cells. Drainage from IF rock (blue lines) became acidic in the early stages of the laboratory testing program but remained neutral with sustained alkalinity levels in field cells after three years of exposure (the flat line alkalinity concentrations in Fig. 5 represent concentrations below laboratory detection limits). Drainage from the 1-kg IV rock samples (red lines on Fig. 4) showed variable degrees of acidification, with two of four PAG samples[3] not realizing their acidic drainage potential during the testing period. In contrast, the 100-kg composite samples (black lines on Fig. 4) consistently produced slightly alkaline drainage pH (around 8) and higher total alkalinity levels than the 1-kg samples. Field-scale drainage quality from IV rock (Fig. 5) corroborated large-scale laboratory tests with consistently neutral pH and elevated alkalinity.

Constituent Leaching Rates

Late-cycle leachate chemistry was used to assess constituent leaching rates. These rates were evaluated on a mass-basis considering the dry weight of the sample in each cell, the amount of water used per leaching cycle, the amount of rock leached, rock density and the frequency of leaching. Table 4 presents the mass-based leaching rates from each test scale for selected constituents of interest. Lithological leaching rates were calculated from the 1-kg cells to obtain an estimate of the expected leaching behavior of each lithology before results from the larger-scale tests became available. Individual contributions from 1-kg cell were factored to most closely simulate the median chemical characteristics for key constituents (principally total sulfur, NP and arsenic content), and consequently similar leaching rates provided by the 100-kg and field cell composite samples. The leaching rates of constituents of interest for each 1-kg cell and the multiplication factors used in deriving the calculated lithological leaching rates are presented in Table 5. The rationale behind multiplication factors is provided in another report (Golder, 2005c). The resulting 1-kg cell leaching rates do not represent compositionally-identical scaled down versions of the 100-kg or field tests but are mathematical approximations. Note that the calculated rate for Goose and Portage IV included 35% contribution from cells that developed ARD during kinetic testing (NP40-03 and G131-01) and 65% from samples that did not (TP372-01 and NP140B-02).

[3] PAG determination from static testing of material



Note on legend: each colored line represents an individual 1-kg sample and each black line represents an individual 100-kg sample

Figure 4. Time series plots of pH and alkalinity for 1-kg and 100-kg kinetic test leachates.

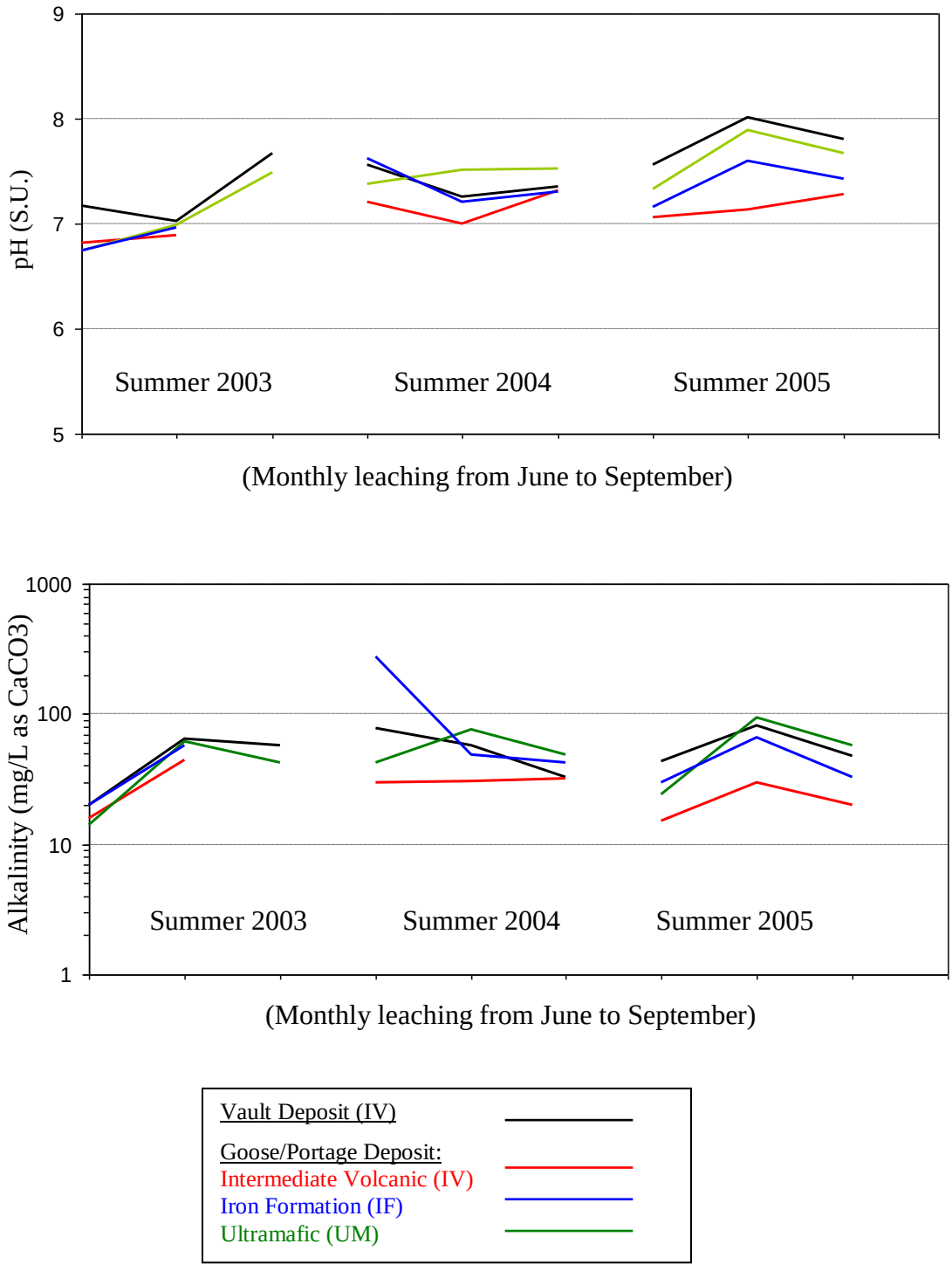


Figure 5. Time series plots of pH and alkalinity for field cell leachates.

Table 4. Summary of leaching rates (mg/kg/week).

Parameter	Field Cells*				100-kg Composite		1-kg Pit Rock (calculated rate)			
	Vault IV	G-P IV	IF	UM	Vault IV	G-P IV	Vault IV	G-P IV	IF	UM
Ca	7.5E-02	1.6E-02	9.3E-02	7.3E-02	1.0E+00	8.3E-01	5.6E+00	2.4E+00	1.4E+00	1.4E+00
Mg	1.2E-02	3.8E-03	2.4E-02	2.3E-02	3.4E-01	2.5E-01	9.5E-01	1.1E+00	7.7E-01	5.5E-01
Alkalinity	1.9E-01	3.8E-02	4.5E-01	3.0E-01	2.0E+00	1.7E-03	1.7E+01	7.0E+00	2.6E-01	6.9E+00
SO4	2.1E-02	1.6E-02	1.4E-01	1.8E-02	2.1E+00	1.9E+00	2.8E+00	1.0E+01	1.5E+01	1.4E+00
As	3.9E-05	1.9E-05	3.7E-06	1.6E-04	3.2E-03	3.4E-03	3.3E-02	6.0E-03	7.8E-04	4.3E-02
Fe	1.3E-04	5.5E-04	2.5E-04	1.9E-04	4.2E-04	4.3E-04	7.3E-03	3.0E+00	5.0E+00	6.8E-03
Ni	7.7E-06	2.4E-05	1.1E-04	1.9E-05	6.9E-06	1.7E-05	1.2E-04	2.8E-02	3.3E-02	1.6E-04

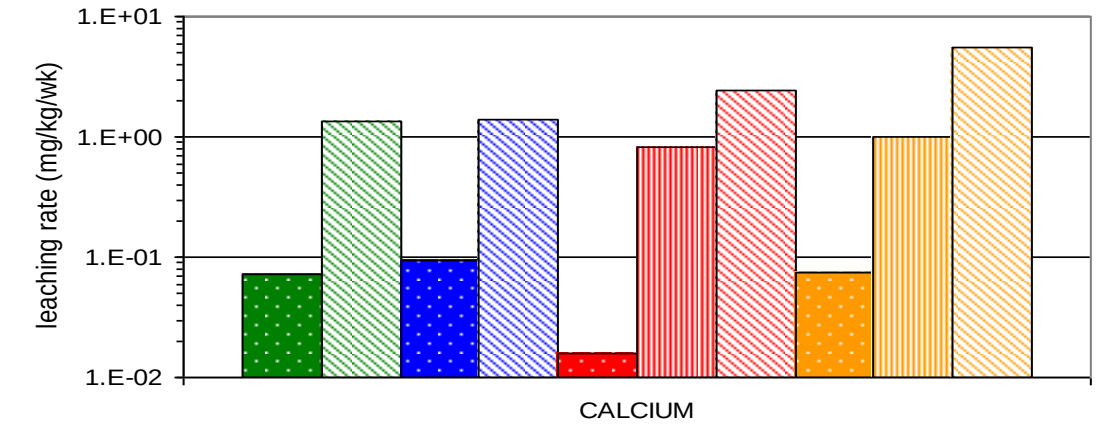
*weekly leaching rate for June to September, (weathering rate not measurable during winter)
G-P: Goose and Portage
all rates in mg/kg/wk

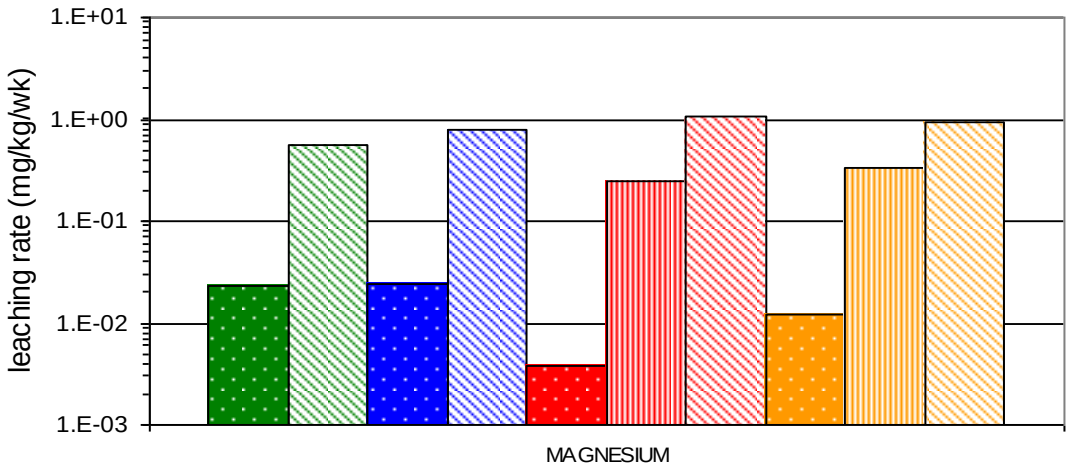
Table 5. 1-kg cell leaching rates and multiplication factors

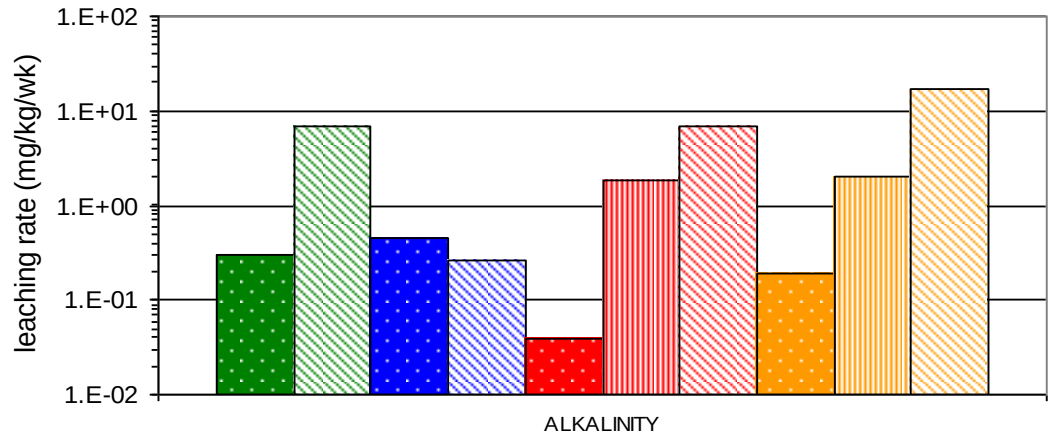
Rock Type	1-kg cell	multiplication factor	Ca	Mg	Alkalinity	SO_4	As	Fe	Ni
Vault IV	V01-02	0.25	4.9E+00	2.5E+00	1.6E+01	6.8E+00	1.8E-03	6.8E-03	1.1E-04
	V23-05	0.75	5.8E+00	4.2E-01	1.8E+01	1.5E+00	4.3E-02	7.5E-03	1.2E-04
G-P IV	NP40-03	0.30	1.0E+00	1.6E+00	2.4E-01	2.7E+01	1.8E-02	8.0E+00	8.0E-02
	G131-01	0.05	9.7E-01	1.8E-01	2.6E-01	2.4E+01	4.1E-03	1.3E+01	7.4E-02
	TP372-01	0.25	1.3E+00	4.2E-01	2.8E+00	1.7E+00	2.0E-03	7.2E-03	3.1E-04
	NP140B-02	0.40	4.4E+00	1.1E+00	1.6E+01	1.4E+00	2.8E-04	6.9E-03	1.1E-04
IF	G103-03	0.05	1.9E+00	1.8E+00	2.4E-01	6.0E+01	5.7E-04	2.5E+01	2.2E-02
	G051-01	0.25	8.3E-01	3.7E-01	3.7E-01	5.3E+00	3.2E-04	2.5E+00	3.5E-02
	TP023-01	0.50	1.9E+00	8.5E-01	2.4E-01	1.1E+01	4.8E-04	1.6E+00	2.7E-02
	TP344-03	0.20	1.3E+00	1.4E+00	2.3E-01	2.9E+01	2.1E-03	1.1E+01	7.7E-02
UM	G108-01	0.90	1.3E+00	4.8E-01	6.6E+00	1.4E+00	2.2E-03	6.8E-03	1.1E-04
	NP40-02	0.10	2.0E+00	1.3E+00	9.8E+00	1.4E+00	4.1E-01	7.1E-03	6.1E-04

G-P: Goose and Portage
all rates in mg/kg/wk

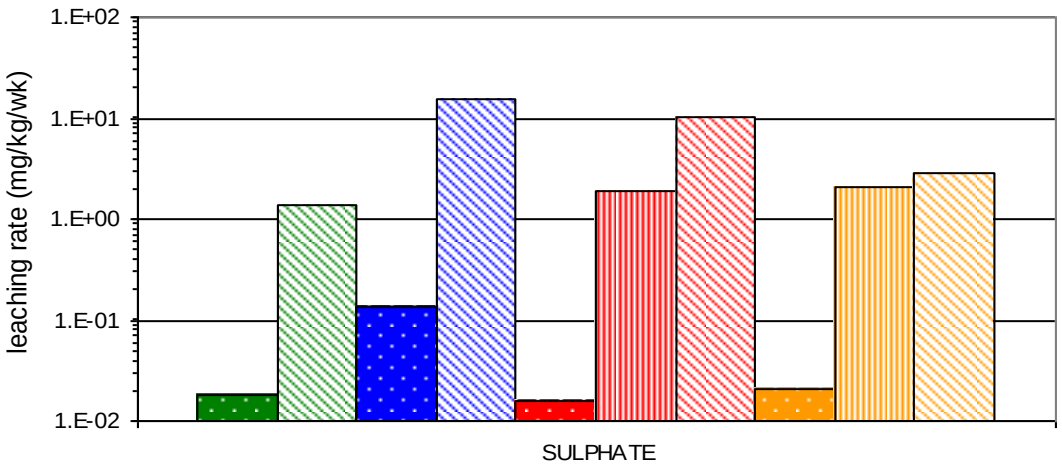
Figure 6 provides graphical representations of leaching rates at various scales for Ca, Mg, alkalinity, sulphate, As, Fe, and Ni.

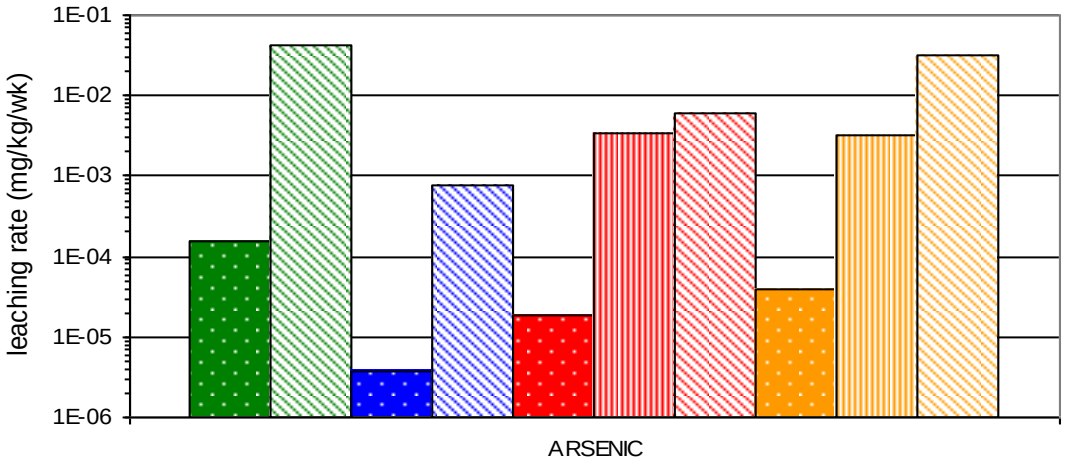

1.E+01
1.E+00
1.E-01
1.E-02
leaching rate (mg/kg/wk)
CALCIUM

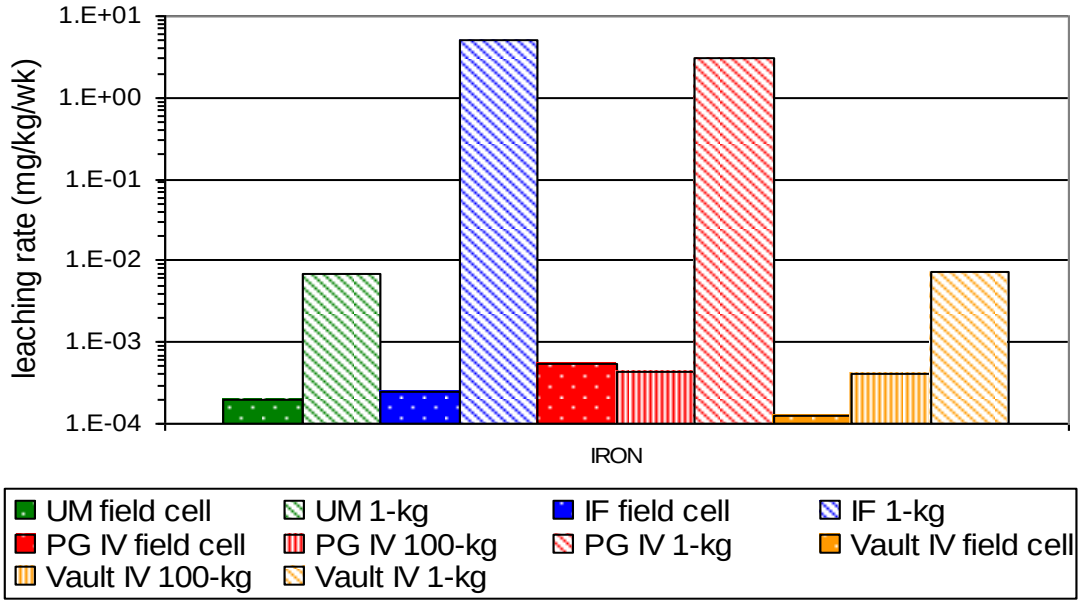

1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
leaching rate (mg/kg/wk)
MAGNESIUM


1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
leaching rate (mg/kg/wk)
ALKALINITY


UM field cell
UM 1-kg
IF field cell
IF 1-kg
PG IV field cell
PG IV 100-kg
PG IV 1-kg
Vault IV field cell
Vault IV 100-kg
Vault IV 1-kg


1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
leaching rate (mg/kg/wk)
SULPHATE


1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
leaching rate (mg/kg/wk)
ARSENIC


1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
leaching rate (mg/kg/wk)
IRON
UM field cell
UM 1-kg
IF field cell
IF 1-kg
PG IV field cell
PG IV 100-kg
PG IV 1-kg
Vault IV field cell
Vault IV 100-kg
Vault IV 1-kg

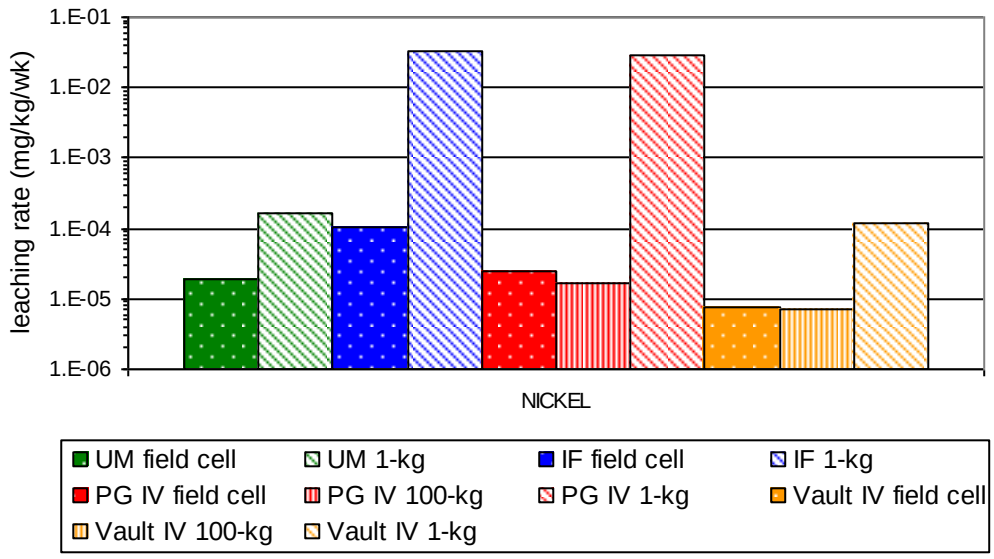


Figure 6. Graphical representation comparing calculated leach rates for alkalinity, Ca, Mg, sulphate, As, Fe, and Ni.

Table 6 presents the calculated difference in leaching rates between 1-kg, 100-kg kinetic tests and field cells for selected constituents. For each constituent of each lithology, the 1-kg:100-kg ratio is the rate from 1-kg test divided by the rate from the 100-kg test. Calculations are the same for the 100-kg:field cell and the 1-kg:field cell ratios.

Table 6. Leaching rate ratios between 1-kg tests, 100-kg columns and field cells.

Constituent	Ratio of Leaching Rates							
	1-kg : 100-kg Kinetic Tests		100-kg Columns : Field Cells		1-kg : Field Cells			
	Vault IV	G-P IV	Vault IV	G-P IV	Vault IV	G-P IV	IF	UM
Ca	5.5	2.9	13	53	74	155	15	19
Mg	2.8	4.3	28	65	79	279	32	24
Alkalinity	8.6	3.8	11	48	91	183	0.6	23
SO4	1.4	5.6	101	117	137	655	111	76
As	10	1.8	82	181	849	321	208	271
Fe	18	7126	3.3	0.8	58	5491	20140	35
Ni	18	1676	0.9	0.7	16	1183	305	8

G-P: Goose and Portage

Flushing Rate and Composite Samples of Mixed ARD Potential: Comparison of the 1-kg and 100-kg Tests. A comparison of leaching rates from the 1-kg and 100-kg tests (IV rock only) shows that leaching rates for major ions (Ca, Mg, alkalinity and sulphate) in the 100-kg cells are typically lower by three to nine times (Table 6). These ratios are somewhat lower than the ratio of flushing rates of the two tests (~15). Fewer minerals are exposed to leaching in the larger scale cell because of lower flushing rate and channeling of flow might increase (further reducing mineral exposure) in the larger cell (as observed by Nichol et al. (2003) in rock piles). A similar behavior is exhibited by As in Vault IV rock (where ARD was not initiated in any of the 1-kg cells). Although mineralogical studies have only identified arsenic with sulfide minerals (pyrite

and arsenopyrite), it is possible that a small proportion of As may be associated with a minor, more soluble phase.

The majority of metals of environmental interest at the site (Fe, Ni are shown as examples but also Zn, Pb, Cr, and Cu, not shown) also show lower leaching rates in the larger scale test, but the variance is larger than for the major ions. For Vault IV rock the difference is slightly more than one order of magnitude (20 times), of similar magnitude as differences in flushing rate, while for Goose/Portage IV cells, the difference is more than three orders of magnitude (the calculated rate being approximately 2,000 to 7,000 times higher). The latter is attributed to the added difference in charge material composition, where the 100-kg composite sample contains rock of mixed ARD potential and is overall non-PAG compared to the calculated leaching rate from 1-kg cells which incorporated accelerated metal release rates because of two of the cells generated ARD during testing. Considering the duration for which alkalinity was sustained in the 100-kg columns (57 weeks of accelerated weathering conditions), results support the proposed waste rock management plan where IV rock of mixed potential will be placed in the RSF to delay the onset of ARD until freezing conditions develop.

Surface Area and Climate: Consideration of the Field Scale Tests. For all rock types tested, field cell leaching rates of alkalinity, major cations and arsenic were one to two orders of magnitude lower (by 11 to 279 times) than 100-kg columns and 1-kg cell leaching rates (Table 6). One exception is the higher alkalinity depletion rate in the 1-kg IF cells compared to the field cells because of the onset of acidic conditions that resulted in faster consumption of alkalinity in the 1-kg cells.

The lower major ion leaching rate observed for field cells is likely caused by a combination of lower surface area available for dissolution, lower moisture content (enhanced channeling effect) and the well-documented effect of lower temperatures on leaching rates described by the Arrhenius equation. Considering the average difference of 13.5 ^{o}C between site and field conditions (summer average temperature at site of 7.5^{o}C compared to 21^{o}C in laboratory), major ion leaching rates are expected to be reduced by a factor of 2 or 3 (Davé and Clulow, 1996; Davé and Blanchette, 1999; Meldrum et al., 2001). The additional reduction in leaching rate is postulated to be caused by the combined effects of lower material surface area and flushing rate in field cells. Surface area and flushing rates are lower in field cells than 100-kg columns by approximately one order of magnitude each, and are lower than the 1-kg cells by two orders of magnitude each. These differences are of similar magnitude as the differences in leaching rates.

The leaching rate of arsenic exhibited a similar pattern as major ions, where field cells had the lowest leaching rate: one to two orders of magnitude lower than the 100-kg columns (82 and 181 times lower for Vault and G-P IV respectively) and two orders of magnitude lower than the 1-kg cells (between 208 and 849 times lower). On the other hand, the leaching rate of the remaining metals of interest exhibited little difference between the 100-kg composites and the field tests, showing less than one order of magnitude difference in leaching rates between the two test scales. The higher flushing rate and larger proportion of fines were expected to produce noticeably, if not considerably, higher metal release rates in the 100-kg samples of IV rock compared to field cells of the same rock type. The similarities between leaching rates reflect the fact that acidic conditions did not develop in either test scale. Differences in metal release rates may become more appreciable if and when ARD conditions develop in field cells. Ratios of metal leaching rates between the 1-kg tests and the field cells present similar variabilities as the ratios between the 1-kg tests and the 100-kg cells. The variability is attributed to the same

factors: 1) different flushing rates for cells that did not develop acidic conditions (Vault IV and UM rock); and 2) a combination of the flushing rate and compositional differences for rock types where acidic conditions did develop in the small scale cells (G-P IV and IF rock).

Scaling up of 1-kg humidity cell leaching rates. Lithological leaching rates from 1-kg cells are consistently higher than those measured in the larger cells. The observed differences can be summarized as follows:

- For alkalinity, major ions and arsenic, a decrease in leaching rate of 5 to 50 times compared to 100-kg cells, and of two orders of magnitude compared to field cells. These differences coincide with differences in flushing rates and are therefore attributed to the flushing regime.
- For metals, a decrease in leaching rate of one to two orders of magnitude is observed in both the 100-kg tests and field tests relative to 1-kg cells for lithologies where ARD conditions have not developed (Vault IV and UM cells). In the other lithologies (Goose-Portage IV and IF), the metal leaching rate is lower by three to five orders of magnitude relative to 1-kg cells, depending on the constituent. The differences are likely attributable to a combination of flushing rate and surface area which together, are of a similar magnitude as the differences between leaching rates.

Based on the combination of results obtained, surface area and water infiltration (flushing) rates appear to exert a greater effect on constituent mobility than reaction temperature under the conditions of the tests completed.

Conclusion

The field cell tests and the calculated 1-kg leaching rates provide adequate end-member brackets of potential leaching rates and timing to onset of ARD. The intermediate scale laboratory kinetic test (100-kg columns) were a useful tool to calibrate leaching rates against the effect of a more homogenous, larger sample size, independent of differences in surface area or site climate. This in-turn provided a stepping-stone in the interpretation of the leaching behavior of materials in-situ. One particularly useful result of this study was the scale up of the Vault IV rock type to estimate the overall bulk drainage quality of the Vault RSF in the short to medium term, until freezing conditions develop in the pile as the proposed permanent ARD control measure.

For major ions, the study results suggest that lower flushing rates and larger surface area have a greater effect on metal leaching rate than temperature. The decreasing trend in major ions leaching rate with increasing test size is believed to be associated with a lower NP depletion rate resulting from lower water flushing rates. The coarser grain size of charge material adds to this effect as less rock per mass is exposed to the water flushing through the cell.

The larger test scales also yielded lower trace metal release rates. For non-acid generating rock, the difference is also attributed to differences in flushing rate and grain size. The effect of lower temperature on metal release rates appeared to be minimal. In cases where the larger cells contained rock of mixed ARD potential, some of which was reactive at the 1-kg laboratory scale, the lower metal release rates (by three to five orders of magnitude) are largely attributed to the increased buffering capacity of larger-scale tests, and, to a lesser extent, to the flushing regime.

Field cell leaching rates can be used to estimate water quality by applying appropriate factors that consider the differences in grain size between the test and expected field conditions. In circumstances where large-scale tests contain a significant proportion of reactive PAG rock mixed with non-PAG rock, the overall metal leaching rates may not be representative of long-term leaching rates in areas of the pile where acidic conditions develop. In these cases, the long-term leaching rates may be more accurately represented by incorporating higher metal release rates derived from smaller test cells that developed acidic conditions.

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