The Meadowbank Gold Mine – Reclamation Planning in an Arctic Environment

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Abstract
The Meadowbank Gold Mine is Nunavut's newest mine, entering production in January of 2010. The project is located 70 km north of the community of Baker Lake and experiences extreme Arctic winter conditions. Annual gold production averages 350,000 ounces from three open pits. Development of the mine required the construction of in-lake dikes to allow the dewatering of lakes that overlie the deposits. Waste rock is deposited on land.

Reclamation planning was incorporated early in mine development planning. This paper describes how the waste rock piles are operated, monitored and how they will be closed and reclaimed. Waste rock types show variable acid rock drainage (ARD) potentials, some of which will require control measures. The control strategies to minimize the potential effects of ARD and the transport of oxidation products include natural freezing of the pile, progressive permafrost encapsulation during operation, and capping with a layer of non-acid generating rock at closure that will act as a cold-insulating cover. The waste rock below the capping layer is expected to freeze, resulting in low seepage rates and the control of transportation of ARD products in the long term. Site monitoring is ongoing to verify anticipated conditions and the validity of the proposed closure plan.

1.1 Introduction
Agnico-Eagle Mines Ltd. (AEM) is owner and operator of the Meadowbank gold mine, Nunavut's newest mine which entered in production in March 2010. The mine produces an average of 350,000 ounces of gold per year at a milling rate of 8500 tonnes per day over a 10-year mine life. Some of the waste rock generate by open pit mining is potentially acid-generating and thus, is managed to control the effects of sulphide mineral oxidation on the receiving environment. Monitoring of the geochemical properties of waste rock produced during operation and on-going validation of the waste rock management plan is a requirement of the Project Certificate issued by the Nunavut Impact Review Board (NIRB) on December 30, 2006, in accordance with the Nunavut Land Claims Agreement Article 12.5.12, and of the Nunavut Water Board Type A Water Licence (NWB) No. 2AM_MEA0815 issued June 9, 2008.

This article describes the waste rock management and monitoring plans developed for the project and the methods of execution of the plans aimed at verifying the validity of the closure plan ahead of the end of mine life.

1.2 Mine Location and Environment
The Meadowbank mine is located on Inuit-owned land, approximately 70 km north of the community of Baker Lake (Figure 1). The mine is a "fly-in/fly-out" operation with an airstrip at the mine and a private all-weather access road linking the mine to Baker Lake. All construction and operating supplies for the project are transported from the south on ocean freight systems to facilities at Baker Lake. The 110-km all-weather road from Baker Lake to the project provides access and allows re-supply while on-site mine access roads connect the open pit areas to the site infrastructure. On-site facilities include a mill, power plant, maintenance facilities, fuel tank farm, water treatment plant, sewage treatment plant, airstrip and accommodations for 550 people. Figure 2 shows the site layout.

Figure 1. Site Location Map

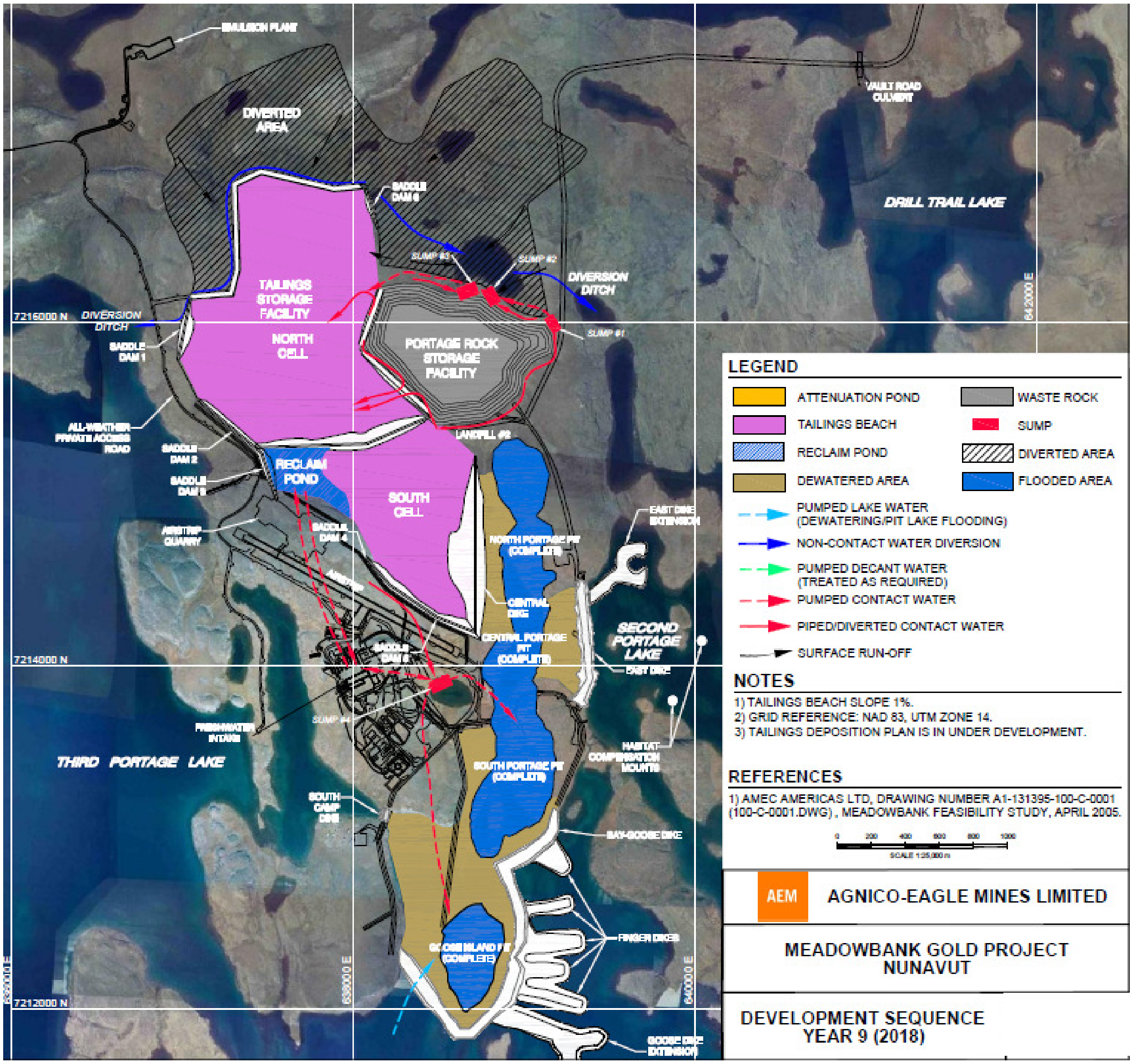

Figure 2. Meadowbank Mine Key Plan

The site is located in an arid arctic environment. It experiences extreme arctic winter conditions, with an annual average temperature of -11°C. The monthly mean temperature ranges from -33°C in January to +12°C in July, with above-freezing averages for only 4 months of the year, generally from June to September. The site is underlain by thick and continuous permafrost, except under lakes where taliks[1] can exist. The site annual average precipitation of 310 mm/year falls mostly as snow and must be managed during spring freshet.

1.3 Regulatory Framework for Closure

AEM is committed to responsible mining practices for the protection of human, wildlife and aquatic life health, and for minimizing impacts on the environment. AEM intends to leave behind a positive community and environmental legacy. This commitment is in agreement with the broad objectives listed in the INAC (2007) guidelines for mine closure, as follows:

[1] Unfrozen ground

- Physical stability: The components of the reclaimed site should be built or modified at closure so that they do not erode, subside or move under extreme design events, and therefore do not pose a threat to humans, wildlife, or environmental health and safety;
- Chemical stability: The components of the reclaimed site should be chemically stable so as to prevent adverse soil, water and air quality effects that might pose a risk to humans, wildlife or environmental health and safety; and
- Future use and aesthetics: The reclaimed site should be compatible with the surrounding lands at the completion of the reclamation activities.

These broad objectives were used to support the identification of closure objectives that are specific to the waste rock pile. These specific objectives are presented in Table 1.

Table 1. Closure Objectives for the Meadowbank Mine

Objective #	Description
1.	Physically and chemically stable lands and waters at the reclaimed Meadowbank sites that are safe for human, wildlife and aquatic life
2.	Lands and waters at the reclaimed Meadowbank sites that allow for traditional uses
3.	Final landscape guided by pre-development conditions and traditional knowledge
4.	Post closure conditions that, where appropriate, do not require a continuous presence of project staff until a walk-away condition is achieved.

The overall approach to the development of the closure plan builds on lessons learned from aspects of closure and reclamation planning at other mining projects in northern Canada (see DDMI, 2009 as an example).

The Interim Closure and Reclamation Plan (ICRP) follows applicable regulatory guidelines, the principles of which are described in:

- Mine Site Reclamation Guidelines for the Northwest Territories (INAC, 2007); and
- Mine Site Reclamation Policy for Nunavut (INAC, 2002).

The ICRP is also subject to the Federal and Territorial Acts and Regulations listed in Table 2.

Table 2. Relevant Federal and Territorial Acts and Regulations

Federal Acts and Regulations	Territorial Acts and Regulations
Arctic Waters Pollution Prevention Act and Regulations	*Nunavut Environmental Protection Act* and Regulations
Canadian Environmental Act and Regulations	*Nunavut Transportation of Dangerous Goods Act* and Regulations
Fisheries Act and Regulations	*Nunavut Mine Health and Safety Act* and Regulations
Navigable Waters Protection Act and Regulations	
Nunavut Land and Claims Agreement and Regulations	
Nunavut Waters and Nunavut Surface Rights Act and Regulations	
Territorial Lands Act and Regulations	

AEM was granted a Type A water license in June, 2008 (NWB, 2008). This license authorizes the use of water and disposal of waste associated with mining and milling activities at the site. The license sets out several conditions with respect to the right to alter, divert or otherwise use water for the purpose of mining. Specifically, in part J, the conditions applying to abandonment, reclamation and closure specify that AEM shall submit an ICRP to NIRB for approval within six months of the start of operations. The plan is to include specific closure and reclamation objectives and an evaluation of alternatives for the closure of each mine component. The development of a closure and reclamation plan is also a requirement of the Nunavut Impact Review Board Project Certificate (NIRB, 2006).

AEM has complied with all governmental policies and regulations pertaining to environmental and socioeconomic issues in developing the Meadowbank Gold Project and have a solid local employment and safety record over nine years of exploration in Canada's Arctic. AEM has been forthcoming with government authorities and Inuit during all aspects of the Project development, and have a good rapport with the local Inuit based on mutual respect and communication. AEM intends to build and operate the mine with integrity, including being safe, environmentally responsible, and beneficial to all parties involved. To this end, AEM intends to balance good stewardship in the protection of human health and the natural environment with the need for economic growth.

2.1 Mining and Waste Rock Management Plans

2.2 Mining and Closure Plans

The Meadowbank property comprises several gold-bearing deposits. The deposits in the current mine plan include Portage, Goose Island and Vault. The Portage and Goose Island deposits are proximal to each other and extend below Lakes. A series of dikes have been constructed to isolate the open pit mining activities from the lakes. Waste rock from these pits is placed in the Portage rock storage facility (Portage RSF) near the Portage deposit, and within the Goose Island and Portage pits toward the end of mining. The Vault deposit is located 7km north of the Portage pit. Mining at Vault will be initiated in 2014. It will also consist of a truck-and-shovel open pit operation. Waste rock produced at Vault will be managed in a separate on-land waste rock storage facility adjacent to the Vault open pit. The current mine plan indicates that the operation will generate approximately 31.8 Mt or ore and 216 Mt of waste rock over the 10-year mine life. All ore is processed at the Portage area mill at a target rate of 8500 tonnes per day (tpd) and tailings are placed as a slurry in a dewatered lake basin adjacent to the mill and to the Portage rock storage facility (RSF) (see Figure 2).

At closure, the surface of the tailing impoundment and the surface and slopes of the Portage RSF will be covered by 4 meters of non acid generating run-of mine waste rock. The thickness of the rock cover is designed to host the depth of active (annual) thaw. The underlying tailings and waste rock are predicted to freeze which is expected to participate in controlling the transport of sulphide mineral oxidation products away from these infrastructures and thus control the effects of ARD on receiving water quality. The waste rock mined at Vault is predicted to be largely non acid generating (Non-PAG) and thus is not subjected to ARD control or environmental mitigation measures. It is not discussed further in this article.

2.3 Geochemical Properties of Waste Rock

Meadowbank waste rock consists of 4 visually distinct groups: intermediate volcanic (IV), iron formation (IF) ultramafic (UM) and quartzite (QZ) although only IV, IF and UM are present in substantial quantities. The ore in Portage and Goose pits is hosted in IF rocks, while it is hosted in IV rocks at the Vault pit. The geochemical properties of all Meadowbank mining wastes have been evaluated through both static and kinetic testing on numerous samples, by various test methods and through multiple stages of testing during the project development stage. These data were used to develop a mine waste management plan that was adequately protective of the environment for authorization by Territorial and Federal regulatory agencies.

The geochemical characteristics of the waste rock have been discussed elsewhere (Bertrand *et al.*, 2006) and are summarized in Table 3 in terms of their potential to generate acid rock drainage (ARD) along with their relative proportion of the total quantity of waste rock generated by mining.

Table 3. Meadowbank Waste Rock Types - Proportions and Geochemical Properties

	Portage and Goose Island			
Rock Type	IV	IF	UM	QZ
Geology	volcanic tuffs, agglomerates (graywacke)	oxide-facies banded iron formation	amphibolite, komateite, mafic to ultramafic	quartzite
Proportion of Portage Area Waste Rock	25%	32%	40%	3%
	100%			
Average Sulphide Content	0.26%	1.2%	0.2%	0.45%
ARD Potential	Non-PAG	PAG	Non-PAG	PAG

2.4 Waste Rock Management

Waste rock and till produced during mining was used in the construction of the mine site infrastructure, including dikes, roads, pad foundations, while some of the waste rock will be put aside for capping at closure (UM rock) and for underwater structures for Aquatic Habitat Compensation. The remainder is placed in a rock storage facility.

As a first step in waste rock management planning, management options were developed for each rock type based on the results of geochemical testing:

- IV: use in submerged environment (dike, lake side or pit side) or RSF below cover
- IF: use in submerged environment (dike, lake side only) or RSF below cover
- UM: unrestricted use and preferred cover material
- QZ: mix with UM for subareal use or in for submerged environment

To date, UM waste rock has been mostly used for site infrastructure foundations and roads along with other quarried material, while some of the IF and IV rock has been used within the tailings basin but most has been disposed in the Portage RSF.

The second step required accounting of the quantity and timing of extraction of each waste rock type on an annual basis, and accounting of the quantity, type and timing of construction material requirements for each infrastructure. To this end, the lithology of waste rock was added to the geological bloc model for each deposit and a detailed account of construction requirements was made based on the most advanced infrastructure designs available at the time.

Construction material requirements were set aside and the balance of waste rock and till was assigned to the Portage RSF and Portage (and Goose) pits for the last years of operation. Table 4 presents a summary of the calculated quantity of each waste type according to their ARD potential, planned use for construction or placed within the RSF or pit during mine life, based on the 2009 mine plan.

Table 4. Portage Area Life-of-Mine Waste Rock Use and Disposal Locations

		2009	**2010**	**2011**	**2012**	**2013**	**2014**
Portage Pit	NPAG (t)	2,196,328	6,684,948	12,105,835	15,584,162	4,851,714	4,883,364
	PAG (t)	2,467,716	9,371,960	11,737,428	9,210,564	4,815,050	7,630,178
	Total Waste (t)	4,664,044	16,056,908	23,843,263	24,794,726	9,666,764	12,513,542
	Till (t)	1,906,870	2,902,242	2,270,077	2,506	0	0
	Ore (t)	726,694	2,665,116	3,591,763	3,806,677	4,721,389	1,140,088
	Waste Destination	1, 2, 4, 7, 10, 18	3, 4, 7, 8, 11,	4, 12, 13, 16	4,16	4, 5	4, 5
Goose Pit	NPAG (t)	0	0	0	0	8,232,406	8,604,586
	PAG (t)	0	0	0	0	3,753,064	2,855,182
	Total Waste (t)	0	0	0	0	11,985,470	11,459,768
	Till (t)	0	0	0	0	2,023,141	0
	Ore (t)	0	0	0	0	601,469	2,064,803
	Waste Destination					5	5

Waste Destination Codes[1]				
	1	East Dike (0.56 Mt)	10	Saddle Dam 4 (0.3 Mt)
	2	Bay Goose Dike Phase 1 (0.76 Mt)	11	Saddle Dam 5 (0.33 Mt)
	3	Bay Goose Dike Phase 2 (1.36 Mt)	12	Saddle Dam 6 (0.3 Mt)
	4	Portage Rock Storage Facility (76.3 Mt)	13	Central Dike (5.45 Mt)
	5	Portage Pit Backfill (33.85 Mt)	14	Airstrip Extension (1.75 Mt)
	6	Stormwater Dike (1.58 Mt)	15	RF1 (0.5 Mt)
	7	Saddle Dam 1 (0.27 Mt)	16	RF2 (0.15 Mt)
	8	Saddle Dam 2 (0.14 Mt)		
	9	Saddle Dam 3 (0.19 Mt)		

The ARD potential of each waste rock pile was then evaluated by calculating the annual and the cumulative ARD potential or Net Potential Ratio (NPR) of the Portage and pit RSFs using equations (1) and (2) respectively:

$$\text{Annual NPR} = \frac{\Sigma(\text{Sum } NP_x * \%_x)}{\Sigma(\text{Sum } AP_x * \%_x)} \qquad \text{(Equation 1)}$$

$$\text{Cumulative NPR} = \frac{(V_A/Vc) * \Sigma(\text{Sum } NP_x * \%_x),}{(V_A/Vc) * \Sigma(\text{Sum } AP_x * \%_x)} \qquad \text{(Equation 2)}$$

where,

x = rock type (IV, IF, UM, QZ);
V_A = total annual volume to be placed in storage area; and
V_C = total cumulative volume within storage area.

Results indicated that the waste stored in each area is predicted to be Non-PAG on an annual basis except for the first few years of production, and that the timing of availability of UM rock for cover is such that this rock will need to be stored temporarily during operation to accumulate the required quantity for use at the end of mine life.

3.1 Execution of the Rock Management Plan

AEM samples every blast hole and analyzes the rejects for sulphur and inorganic carbon content using an on-site Leco furnace. Results are compared against previously-established, site specific cut-off criteria derived from earlier geochemical studies, to differentiate Non-PAG from PAG materials. The sulphur (S) analysis is converted into a Maximum Potential Acidity (MPA) value by multiplying S wt% by 31.25 which yields an MPA value in kg $CaCO_3$ equivalent. The Total Inorganic Carbon (TIC) analysis is similarly converted into a Carbonate Neutralization Potential (NP) by multiplying the TIC wt% reported as %CO_2 by 22.7 which yields an NP value in kg $CaCO_3$ equivalent. The Net Potential Ratio (NPR) for the blast hole drill cutting sample is then calculated as follows: NPR = NP/MPA.

The mine geology staff uses the calculated NPR and gold assay values to identify the following categories of materials: "waste PAG", "waste Non PAG" and the various grades of gold ore, from low to super high grade. The mine surveyor uses this information to delineate the dig limits within the blasted rock pile to guide the shovel and loader operators in directing where the rock is to be taken (Photo 1). The shovel and load operators are given specific directives and/or maps of the blasted rock types and their destination.

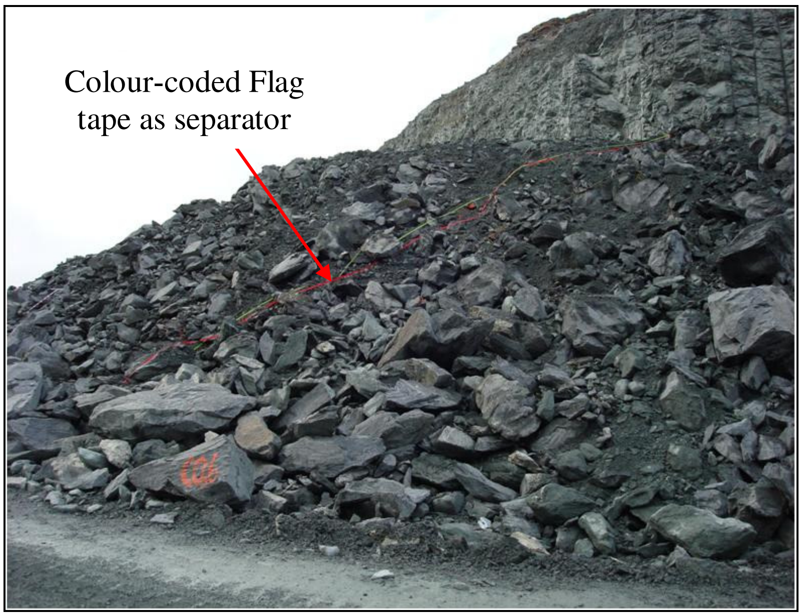

Photo 1. Differentiation of PAG and Non PAG rock after a blast based on analytical data and blast pattern

To date, most of the Non PAG rock has been used for construction of the dikes, dams, roads and pads. Some of the PAG rock has been used in the footprint of the Tailings Impoundment Area but the majority of this rock was sent to the Portage RSF (15.1 Mt). Photo 2 shows the configuration of the waste rock storage facility in August 2011, and Photo 3 shows active dumping on the facility in December 2011.

Photo 2. Looking south-west, view of Portage RSF (foreground) and west basin of tailing impoundment


Photo 3. Active dumping of waste rock on the RSF

Changes in market value increases resources and changes to the mining plan. Additional waste rock storage areas are now being considered, including an area to the north of the existing Portage RSF for temporary storage of UM rock for cover and increasing the quantity of waste rock to be placed in both the Portage and Goose Island pit, leaving an adequate volume and depth of water in the flooded pits at end of mine life for fish habitat creation. The final closure plan and objectives remain unchanged.

3.2 Performance Monitoring

Confirmatory sampling and geochemical analysis of waste rock is on-going since mine start up. In 2010, a total of 52,752 production samples were assayed to differentiate between PAG and Non PAG rock. The analytical data and resulting ARD classifications are logged in the Meadowbank GEMCOM database. To validate the method used, 150 samples from production drill holes in all rock types were sent to an accredited commercial laboratory (an external laboratory) for acid base accounting (ABA) analysis using the Modified Sobek Method (MEND, 1991) and for metal leaching using the Shake Flask Method (Modified ASTM D3987).

RSF contact water quality and pore space air temperature are also being monitored to validate or update the closure plan. This is done by installing thermistor stings in boreholes through the rock pile, drilled for this purpose. In addition to the numerous thermistors installed on the property to monitor ground temperature, thermistor strings are currently being installed on the first bench of the Portage RSF on the southern edge of the pile to monitor the temperature in the rock pile (Photo 4). Thermistor installation and temperature monitoring in the RSF, tailings, berms and dikes will continue throughout the operational mine life.

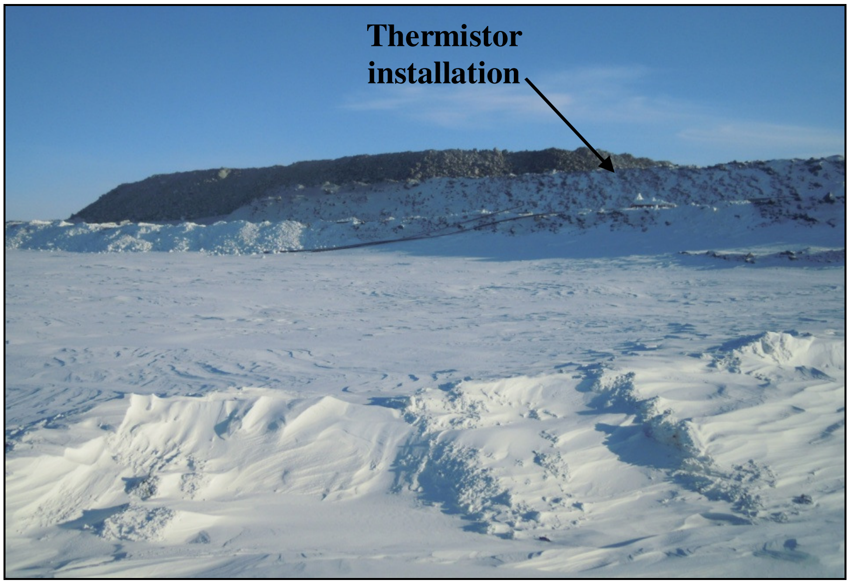

Photo 4 Thermistor installation on first bench of RSF.

No seeps have been observed to date at the Portage RSF, however a depression of the land surface at the base of the north edge of the RSF accumulates water during freshet (Photo 2) where surface water is in direct contact with the waste rock, parts of which are PAG. Water quality of this pool is similar to that of natural area runoff over bog terrain although some increasing trends are visible. The water has a slightly acid pH value and low concentration of chemicals typical of organic-rich bog waters at site, but the water is more turbid with higher concentrations of suspended solids, presumably from contact with the freshly blasted rock, and a trend of slightly increasing chemical constituents was observed in 2011. Table 6 shows the water quality of monthly grab samples of water collected at this pool (monitoring location SW-6).

Table 6. Concentration of Select Parameters in the Pool at the Base of the Portage RSF

	Date	19/06/2011	01/08/2011	06/09/2011	04/10/2011	01/11/2011
	Unit	WR-SW-1				
pH		5.98	6.58	6.32	6.97	6.6
Alkalinity	mg $CaCO_3$/L	16	31	46	35	44
Sulphate	mg/L	< 1	10	24	49	37
Hardness	mg $CaCO_3$/L	na	42	55	67	82
TDS	mg/L	18	56	92	na	na
Arsenic (As)	mg/L	< 0.005	< 0.0005	0.0028	0.0016	0.0016
Iron (Fe)	mg/L	< 0.05	0.94	1.4	2.2	2.2
Manganese (Mn)	mg/L	0.074	0.32	0.56	0.67	0.67
Nickel (Ni)	mg/L	< 0.005	0.0186	0.0304	0.0559	0.0619
Ammonia	mg/L	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Nitrate	mg/L	0.18	0.07	< 0.01	0.32	0.27

na: not analyzed

4.1 Conclusion

The transition from project planning to mine operation was characterized by frequent mine plan changes. Nonetheless, some of the planning items and mine waste management methods remain effective in segregating the waste according to its ARD potential and use at the site, which is required to meet closure commitments at end of mine life at controlled costs. Lessons learned at Meadowbank highlight the usefulness of the following in waste rock management planning:

- Completion of a comprehensive geochemical characterization of mine wastes at the project planning stage which provided robust data that could be relied upon through changes in mining sequence.
- Incorporation of lithology in the bloc model to allow the accounting and determination of timing of availability of mine wastes for the different purposes at site, and to formulate an environmentally protective closure plan for waste rock facilities.
- Accounting of material requirements for construction of the various infrastructure with adequate accuracy.
- Continual monitoring of management performance indicators to validate the management strategy or modify it with sufficient lead time to avoid environmental effects and minimize operational delays and costs.

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Acronyms

ABA	Acid Base Accounting
AEM	Agnico-Eagle Mines Ltd.
ARD	Acid Rock Drainage
DDMI	Diavik Diamond Mines Incorprated
ICRP	Interim Closure and Reclamation Plan
IF	Iron Formation Rock
INAC	Indian and Northern Affairs Canada
IV	Intermediate Volcanic Rock
MPA	Maximum Potential Acidity
NIRB	Nunavut Impact Review Board
Non-PAG	Not-Potentially ARD Generating
NP	Neutralization Potential or Acid Neutralization Potential
NPR	Net Potential Ratio NPR=NP/MAP
NWB	Nunavut Water Board
QZ	Quartzite Rock
RSF	Rock Storage Facility
TIC	Total Inorganic Carbon
UM	Ultramafic Rock