The use of NSR during the Fedorovo ARDML evaluation program

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ABSTRACT

In the assessment of the acid rock drainage (ARD) and metal leaching (ML) potential for a mine the standard approach is to assess each lithology, in conjunction with alteration and/or ore type. These variations in lithologies are then referred to as material types and further sub-classified into either reactive or inert waste materials, and ore in order to define their disposal or storage requirements. However, these materials are often classified in the early stages of a project at the prefeasibility or feasibility stage and remain classified as such for the duration of the geochemical assessment. Subsequent changes in project economics can lead to the need for a reclassification of materials, but it is often difficult to relate these back to samples in the geochemical testing. During the recent feasibility study of the Fedorovo Project, located on the Kola Peninsula, in the North West of Russia, net smelter return (NSR) was added to the material type classification system to address this issue.

The NSR value is determined from the economic metal content of the rock and is generally readily available in the early stages of a project from the exploration and resource drilling program. By utilizing the NSR values it is possible as the economics of the deposit are finalized to relatively easily reclassify materials as either waste, possible ore or ore.

This study also demonstrated the potential for the leaching of metals at low levels and under nonreactive conditions. Combining this potential with the need to protect fisheries resources required the Project to have a comprehensive water management strategy.

This paper will present results from a current ARDML study and show how the NSR value was utilized in defining both the material types and resultant implications for waste management both during the operation of the mine and at closure.

Additional Key Words: Acid Rock Drainage Metal Leaching (ARDML), Platinum Group Minerals (PGM), Copper, Nickel, Net Smelter Return (NSR), Fedorovo

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INTRODUCTION

The risk of long term contaminant release from mine wastes probably poses one of the greatest risks to a mining operation, as the potential for contaminant releases can far exceed the life of the mine and can potentially generate significant ongoing obligations for environmental controls well after closure. To address this risk and its post-closure financial consequences geochemical evaluations of proposed mining projects are now common place. Barrick Gold Corporation has long recognized this need and been committed to proactively predicting and developing measures to minimize the potential impact of any operation for all phases from exploration through to post-closure.

Typically, a geochemical assessment to fully evaluate these impacts is often a lengthy exercise, due to some of the testing required, and this will often see the testing continue over several phases of the evaluation of a mining project. As a result, as the economics of the project are refined or changed, there is a potential for materials to be reclassified.

Generally, for geochemical assessments materials generated by mining operations are simply categorized as waste rock, ore or processing wastes. They may then be further subcategorized by lithology and then alteration to give a specific material type. These specific material types are then subjected to geochemical assessment and evaluation. However, these material types are generally defined in the early stages of the mining project when the economic boundaries between waste rock and ore are least well defined.

To overcome this problem on a recent geochemical assessment of the Fedorovo Project the additional categorization of Net Smelter Return (NSR) value was included in the material type classification system. The inclusion of this value enabled the geochemical study to commence normally, but also allowed for the easy reclassification of materials as the economics of the deposit were finalized.

NET SMELTER RETURN

Often, mines produce concentrates that are then sold on for refining before the full market value of the commodity can be realized. The NSR value is defined by Wellmer et al (2008) as the metal value of the concentrate produced by the mine less smelter treatment costs (T/C) and losses, refining charges (R/C) and freighting costs. All are then corrected for the concentration factor (i.e. how many tonnes of ore were required to produce 1 tonne of concentrate) this then gives an NSR value, in $ per t of ore. This is illustrated in the schematic of Figure 1.

From the NSR value mining and processing costs are then deducted to determine the viable ore material. However, the assignment of an NSR value does not necessarily need to be restricted to just the ore materials; often the waste rocks also contain a degree of commodity value that enables them to also be assigned an NSR value, even though in reality they may never be considered as ore. In addition, the assignment of NSR values to all materials enables current sub-economic possible ores to be readily defined. These can then be stockpiled independent of the ore and separate from the waste rock to allow for their proper management from an environmental perspective and for future processing in the event that economics become more favourable, which sometimes occurs when a mine is coming to the end of its life.

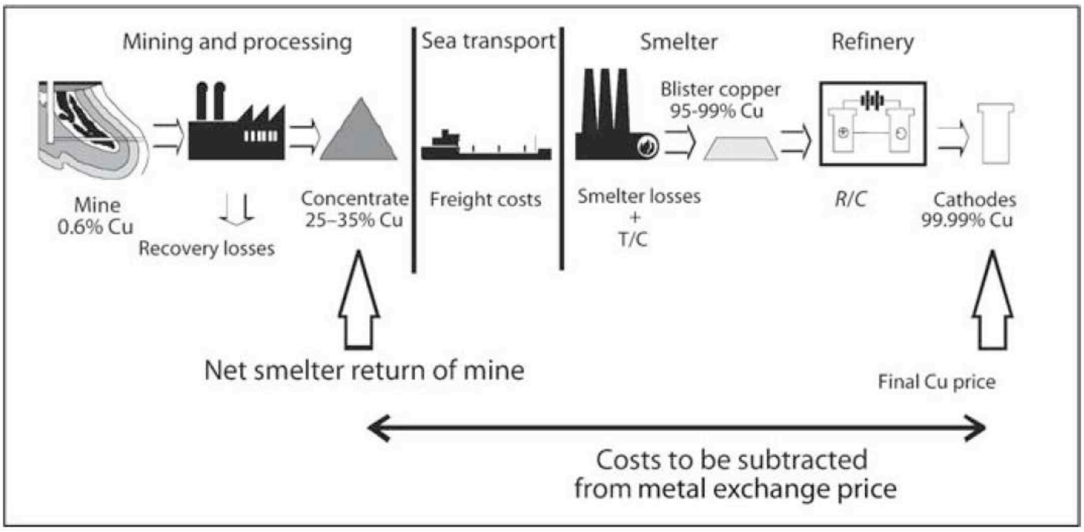


Figure 1: Schematic of NSR definition for a typical copper operation (Wellmer et al, 2008)

Given that the NSR value of the material is going to change minimally over the engineering phases of a project, especially compared to the mining and processing costs, using NSR values enables the geochemical assessment process to be initiated early, as is necessary. Then, towards the completion of the project engineering, materials can finally be classified with confidence as waste, possible ore or ore. For the Fedorovo Project, NSR value increments of \$2/t were used to select samples to initiate ARDML testing.

FEDOROVO PROJECT

The Fedorovo Project is a low sulfide chalcopyrite-pentlandite-pyrrhotite type deposit with an average sulfide content of about 1 wt%. It occurs with the Fedorova Tundra intrusive massif in the NE corner of the Precambrian Baltic (Fenno-Scandian) Shield (see Figure 2). The regional characteristic of the feature is a widespread long-living magmatic activity (Archaean to Paleozoic age) and intrusive-associated copper, nickel, platinum group minerals (PGM), chromium, iron, titanium, apatite and rare-earth-elements mineralization. The nickel, copper and PGM mineralization of the Fedorovo Project is associated with mafic and ultramafic differentiated layered magmatic complexes of gabbro-norite-harzburgite formation. The Fedorova-Pana intrusive has a distinctive inter-formation position on the boundary of the Imandra-Varzuga Proterozoic greenstone belt and Archaean Keivy block; it is the largest layered complex of the province, amongst it ‘relatives’, that are the other mining operations within the structure; these are Monchepluton, Penikat group (Suhanko Project), Keivitsa and Volchetundra.

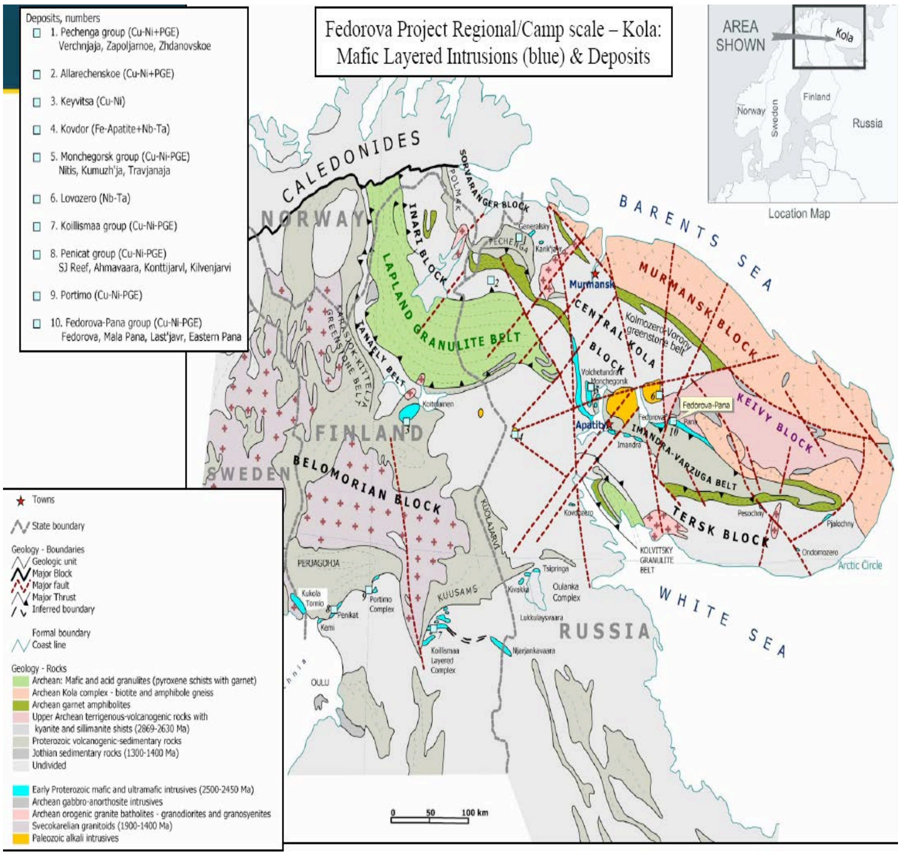


Figure 2: Location and regional geology of the Fedorovo Project

As currently envisaged, the Fedorovo Project will comprise two open pits (East and West) and a concentrator that will produce a copper-nickel-platinum-palladium concentrate.
Within the open pits, three major lithologies have been identified Gabbro-Norites, Pyroxenites and Amphibolites, together with four minor lithologies Upper Gabbros, Olivines, Gneisses and Diorites (see Table 1).

Table 1: Generalized lithologies of waste rock, possible ore and ore of Fedorovo open pits.

DESCRIPTION	MAJOR LITHOLOGIES			MINOR LITHOLOGIES *	TOTAL
	Gabbro-Norites	Pyroxenites	Amphibolites		
Waste Rock	30%	18%	8%	9%	**65%**
Possible Ore	2%	1%	0%	0%	**3%**
Ore	19%	6%	4%	2%	**31%**
Total	**50%**	**25%**	**12%**	**12%**	**100%**

*** Upper Gabbros, Olivines, Gneisses and Diorites**

SAMPLE SELECTION

The initial samples selected for ARDML testing covered both open pits and four lithologies (Gabbro-Norites, Pyroxenites, Amphibolites and Upper Gabbros) within the open pits. However, a problem with these samples was the fact that they only represented the least problematic 40% of the waste rock likely to be removed from the open pits. Primarily, this was due to a conscious effort to select samples with as little mineralization as possible. As will be clearer later, proceeding to test these samples might well have led to the erroneous conclusion that all waste rock removed from the Fedorovo open pits would be non-problematic from an ARDML perspective.

Fortunately, the deficiencies of these initial samples were recognized before testing commenced and they were replaced with new samples that better represented all of the materials that would likely be removed from the open pits and then managed to protect the environment. Like the initial samples, the new samples covered both open pits. However, unlike the initial samples, the new samples covered seven lithologies (Gabbro-Norites, Pyroxenites, Amphibolites, Upper Gabbros, Olivines, Gneisses and Diorites) within the open pits as opposed to four. The new samples also represented 100% of the waste rock likely to be removed from the open pits, which was due in large measure to the inclusion of NSR value among the sample selection criteria.

In addition, the new samples reflected both the sulfide percentage (indirectly achieved via copper plus nickel percentage due to the non-availability of sulfide data) and the NSR values of the materials. Specifically, this was accomplished by ensuring that for each of the three major lithologies there were at least two samples for each $2 NSR value increment between NSR value -$2/t and NSR value $14/t. One of these samples represented the mean copper plus nickel percentage of all core samples of that lithology in that NSR value increment and the other represented the mean plus two standard deviations copper plus nickel percentage.

For the four minor lithologies, a total of three samples were selected for each lithology such that one represented the mean copper plus nickel percentage of all core samples of that lithology, the second represented the mean plus one standard deviation copper plus nickel percentage and the third represented the mean plus two standard deviations copper plus nickel percentage. For the minor lithologies there was no attempt made to reflect the NSR values of the materials likely to be removed from the open pits.

GEOCHEMICAL ASSESSMENT

For the geochemical assessment a standardized suite of four static tests were utilized. These were:

- Whole rock assessments: to determine the maximum concentration of elements that the other tests could then be compared against.

- Modified US-EPA 1312 contact tests: to evaluate the readily available salts of the materials.
- Acid Base Accounting (ABA): to assess acid producing and consuming potentials.
- Single Static Net Acid Generation tests: to investigate the maximum potential of acid and metal release.

Whole Rock Assessments

The whole rock assessments were undertaken at The Russian Academy of Sciences, VI Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow, using a standard strong acid digestion method, with HF, HNO_3 and HCl, then subsequent analysis by ICP-OES.

Potential problematic elements (PPE) were identified by comparing these assays to average crustal abundances. As a rule of thumb any element that occurs at greater than three times its average crustal abundance is generally regarded as a PPE in environmental geochemistry.

Modified US-EPA 1312 Contact Tests

In the modified US-EPA 1312 contact tests three parts liquid are contacted with one part solids for 24 hours (in the original test the ratio is 20:1 liquid to solid) and the generated leachate is then recovered for analysis. Using a lower liquid to solid ratio improves the detection limit of the test as the released salts are dissolved in a lesser volume of water. Also as the core samples are freshly prepared only a minimal quantity of oxidised salts were expected from the samples and so the best detection limits are paramount. In the modified test the extractant deployed was deionised water, as this is easy to standardise (in the USEPA test the extractant is a pH buffered deionised water intended to simulate potential landfill leachates). Testing and analysis was undertaken at The Russian Academy of Sciences, VI Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow.

Acid Base Accounting

ABA assesses the differences and ratios of potentially acid forming sulfur minerals and potentially neutralising carbon minerals within the samples. The values of both total and sulfide sulfur were determined, together with the carbon contents, both total and inorganic. A Leco furnace was utilised for the analysis and works by the high temperature combustion of the sample in an oxygen rich environment. The formed sulfur dioxide and carbon dioxide products are then determined by integrated spectrometry and then internally back calculated to give source values.

Testing and analysis was undertaken at The Russian Academy of Sciences, AA Baikov Institute of Metallurgy, Moscow.

Single Static NAG

The Single Static NAG test is utilised to assess the full acid generation potential of the sample in the presence of a highly vigorous oxidising reagent, hydrogen peroxide. The test enables an evaluation of the maximum oxidised acid production, complete with any potential neutralisation, of the sample. From the variation of the test used a portion of the generated leachate was removed to provide an assessment of PPE mobilisation or NAG_{metals}. Testing and analysis was undertaken at The Russian Academy of Sciences, VI Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow.

RESULTS AND DISCUSSION

Results from the whole rock assessments indicated that arsenic, cadmium, chromium, copper, magnesium, nickel and sulfur were all PPE in all lithologies and that the concentrations of these PPE increased as NSR value increased. This was not too surprising as the sulfide and other associated mineralisation is disseminated throughout much of the deposit and the natural abundance of most of these elements is low. Results from the assessment suggest that both copper and nickel dissemination have a good correlation with the sulfur and that iron, present in the major minerals of the resource, also follows a similar trend, see Figure 3.

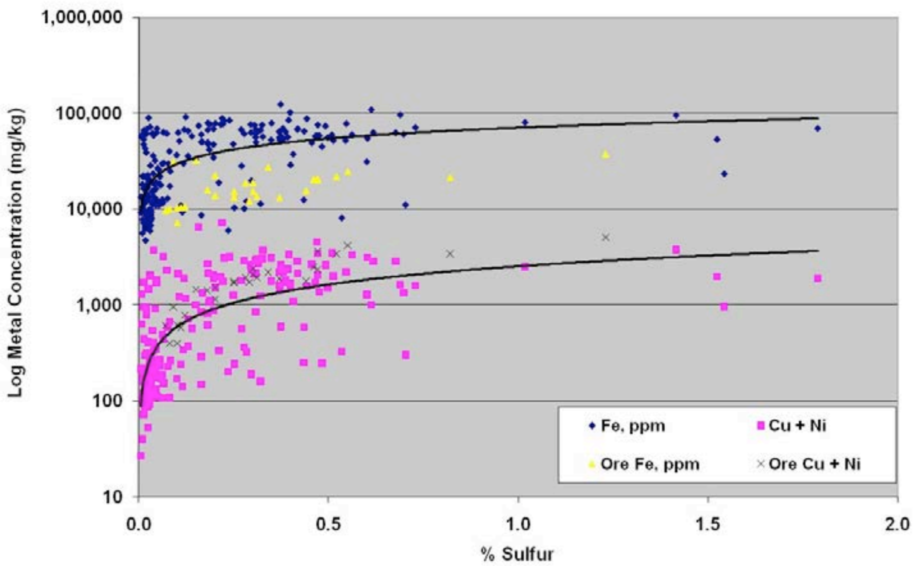


Figure 3: Relationship between copper, nickel, iron and sulfur

The modified US-EPA contact tests suggested that copper, molybdenum and vanadium could potentially be released immediately from Project waste rock and ore storage facilities (see Figure 4). However, the pH of any contact water is expected to be near neutral and so the potential problem would be one of low level metal leaching. As the released metals would be at low concentrations they would not normally be cause for concern, but when assessed against the even lower maximum allowable concentrations for fisheries waters applicable to the Project area (0.001 mg/L for copper, molybdenum and vanadium) concern is heightened. The fact that the Project area is both a headwaters area and a mineralized area only increases this concern because there is minimal capacity in potential receiving waters for additional metals loading. On the positive side, the fact that neither molybdenum nor vanadium were consistently identified as PPE in the whole rock assessments suggests that their potential for long-term impact will not be significant.

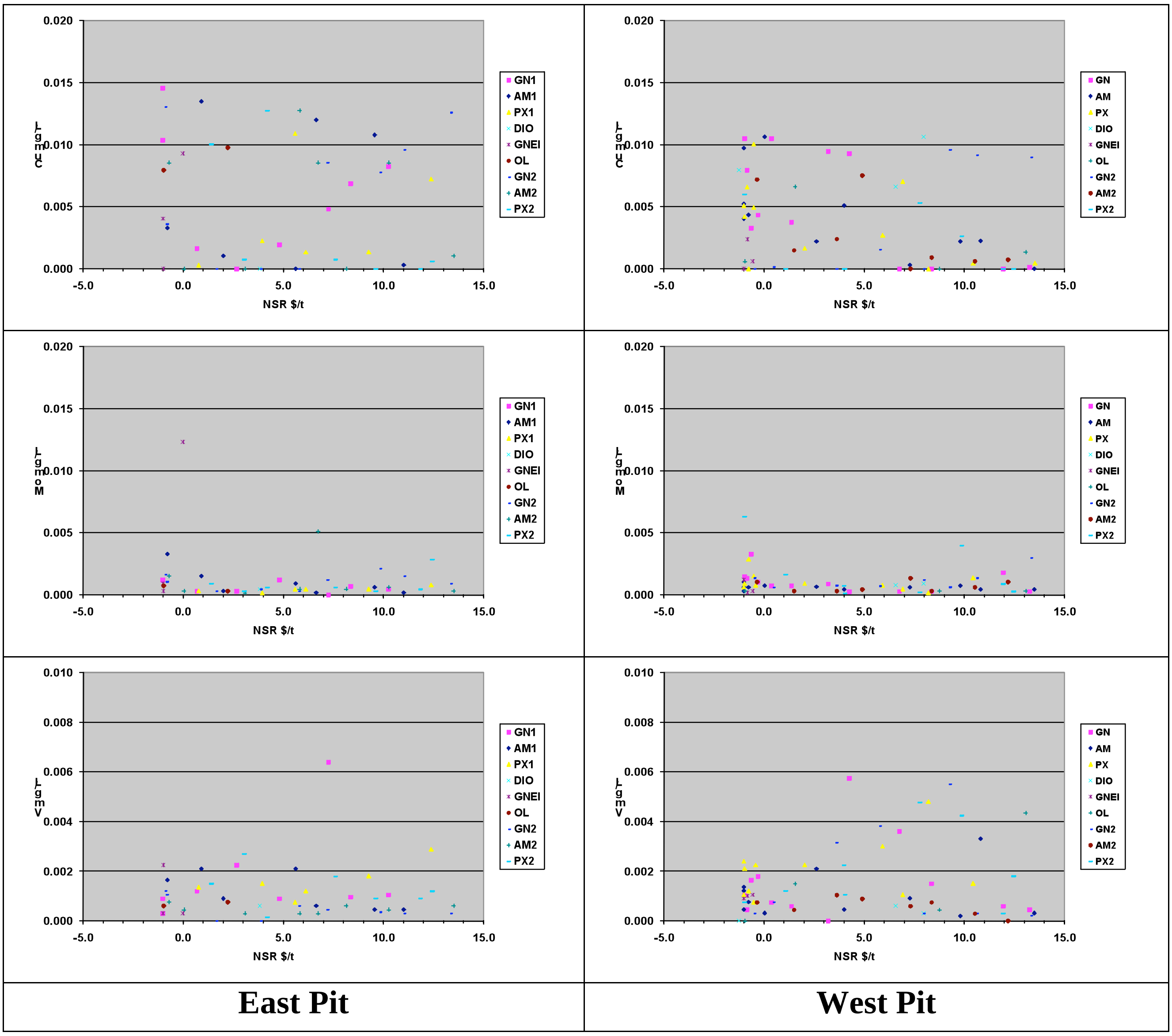


Figure 4: Selected metal releases from modified US-EPA 1312 contact tests

The ABA results indicated that sample oxidation was minimal and as the sulfur values were low, nearly all samples were below 1% and the majority were below 0.3%, both as total sulfur and as sulfide sulfur, there was minimal acid potential. However, nearly no neutralizing carbonates were detected. From an ARD perspective, the tests indicated a greater risk for materials from the east pit and, in general, the very low NSR samples (i.e., <$0/t) gave the least potential for ARD. Only a very few samples could be clearly defined as potentially acid forming.

The low sulfur values observed in the ABA results were also reflected in the results of the Single Static NAG testing and the majority of the low value NSR (<$0/t) samples tested returned near neutral pH values and showed very little ARD potential (<5kg H_2SO_4 equivalent per tonne). In addition, a potential for long-term PPE release was noted, but only for copper and nickel (see Figure 5). Again, concentrations are expected to be low and the pH to be near neutral or approximate that of the natural background. The fact that the generated effluent is near neutral relates to the dominant mineral phase being pyrrhotite and not pyrite. Pyrite has a greater capability for producing acidic discharges. Finally, it is important to note that the Project area receiving environment is not as sensitive to nickel as copper, as the maximum allowable concentration for fisheries waters is set at 0.010 mg/L.

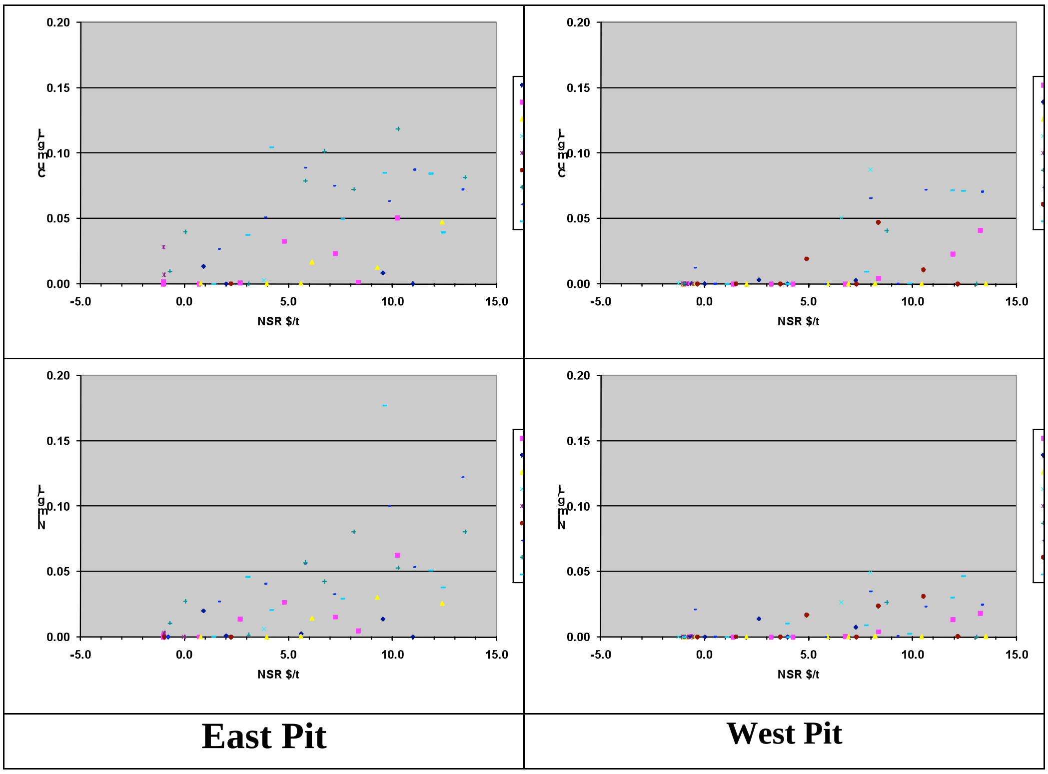
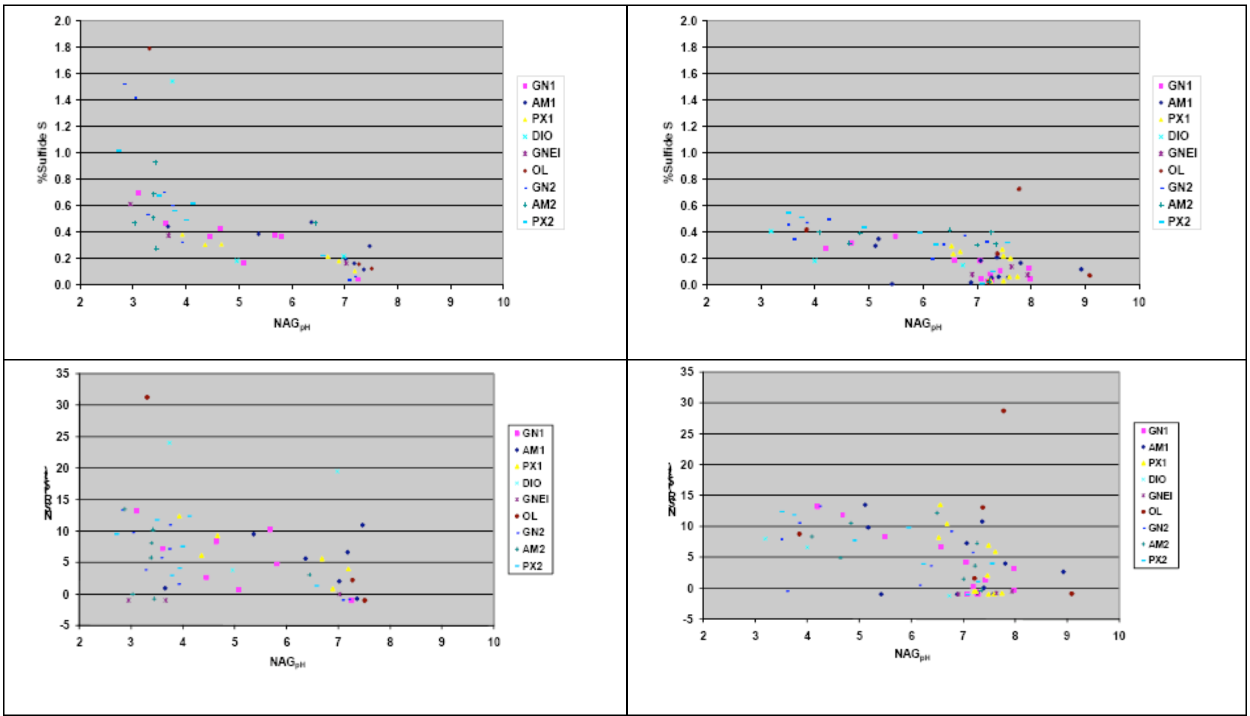


Figure 5: Release of nickel and copper from the NAG test

For design purposes, the results of the geochemical testing suggested that a cut-off value of 0.2% sulfide sulfur was a threshold of reactivity within the deposit (i.e. above this value materials tested generally became problematic). This value of sulfide sulfur equates to an NSR value of approximately $0/t, which means that approximately 30% of all materials to be moved, including ore, or approximately 43% of all waste rock can be considered to be potentially problematic. This is illustrated in Figure 6 and Table 2.



East Pit	**West Pit**

Figure 6: Sulfide sulfur and NSR value versus Single Static NAG test pH

Table 2: Generalized lithologies of waste rock, possible ore and ore of Fedorovo open pits.

NSR $/TONNE	DESCRIPTION	MAJOR LITHOLOGIES			MINOR LITHOLOGIES *	TOTAL
		Gabbro-Norites	Pyroxenites	Amphibolites		
< $0	NAF waste rock	13.0%	7.5%	3.4%	5.5%	29.4%
$0 to $6	PAF waste rock	16.9%	10.7%	4.3%	4.0%	35.9%
$6 to $8	Possible Ore	2%	1%	0%	0%	**3%**
$8 to $12	Low-grade Ore	4%	2%	1%	1%	**7%**
$12 to $14	Mid-grade Ore	2%	1%	0%	0%	**3%**
> $14	High-grade Ore	13%	4%	3%	2%	**21%**
Total		**50%**	**25%**	**12%**	**12%**	**100%**

*** Upper Gabbros, Olivines, Gneisses and Diorites**
NAF - Non-Acid Forming
PAF - Potentially Acid Forming

Overall, the results of the geochemical testing indicated that while the deposit was not necessarily acid generating it had the potential to generate a low level metaliferrous effluent, and that this could potentially start immediately and continue indefinitely. From a literature review this was not found to be uncommon, however, very few published examples were found. The literature review focused on low grade copper-nickel deposits, in particular in the high latitude Northern hemisphere as these were deemed to be akin to the Fedorovo resource both in terms of mineralogy and environmental conditions.

Results published for the Enonkoski and Hitura mines in Finland gave an indication of near neutral pH releases but with low level metals. Enonkoski Mine was in operation between 1984 and 1994. During its operation 6.7 Mt of ore with 0.78 % nickel and 0.22 % copper were mined. The release chemistry from a tailings heap at the site is shown in Table 3:3.

Table 3: Mine water chemistry of Enonkoski Mine in Finland, metal vales in μg/L (Wolkersdorfer & Bowell, 2005)

	pH	Al	Co	Cu	Fe	Mn	Ni	S	Zn
Enonkoski Ni-Cu Mine, tailings heap surroundings (2002)									
Leachate (n=1)	6.4	10	35	<0.5	12.9	3040	1220	297	15
Discharge* (n=1)	7.5	8.5	0.5	0.7	0.68	108	142	76.5	8.6

n refers to number of samples
* Discharge from natural wetland into lake

The Hitura Mine has operated since 1970. It produces 2,200 t/a of nickel metal and is a 650,000 t/a underground operation. To date 14 Mt of ore containing 0.6% nickel has been mined. The tailings facility contains 12 Mt with 0.2% nickel, 0.15 % copper and 0.2-18% sulfur. The following table provides details of water chemistry around the mine.

Table 4: Water chemistry around the Hitura Mine (Wolkersdorfer & Bowell, 2005)

Hitura Ni-Cu Mine	pH	SO_4^{2-}	Cu	Fe	Ni
Mine water, 1998–2000 and 2002–2004	7.5	499	–	0.40	0.15
Settling pond in the facility, 1989–2001	6.1	4134	0.04	1.80	2.33
Discharge*, 1989–2001	6.2	235	0.02	1.17	0.17
Kalajoki river**, 1989–2001	6.4	17.0	0.02	1.19	0.01
Kalajoki river (upstream, uncontaminated), 1989–2001	6.5	7.93	0.02	1.17	0.01
Contaminated groundwater, 1999*** (*n* = 31)	5.7	4320	0.04	51.7	3.65
Uncontaminated groundwater, 1999*** (*n* = 42)	6.3	55.5	0.01	5.90	0.02

*Discharge to the Ainasoja brook after settling; **Below the discharge from the Ainasoja brook; ***Heikkinen et al. 2002

The Raglan Mine has been operating since 1997, it produces 26,000 t/a nickel concentrate and 6,700 t/a copper concentrate. It is a 1.3 Mt/a underground and open pit operation.

Rinker et al (2003) published the results of humidity cell tests conducted on selected samples representing the various rock types from the Raglan Mine, these included Gabbro, Argillite, Pyroxenite and aggregate rocks. The tests were conducted to assess the leaching characteristics of different types of waste rock under neutral pH conditions. In general, the results show that both nickel and sulfate exhibited relatively steady state concentrations in the leachate after ten weeks of testing. As a result, the mean, steady state nickel and sulfate concentrations were calculated as the average value from week 10 to week 69 and these values are presented in Table 5, together with maximum observed values.

Table 5: Kinetic cell data from Raglan mine waste rock (Rinker et al., 2003)

Rock Type	Peak Concentration		Mean, Steady State Concentration	
	Nickel (mg/L)	Sulphate (mg/L)	Nickel (mg/L)	Sulphate (mg/L)
Standard Leach Test				
Gabbro	0.02	3	<0.010	0.6
Argillite	0.16	17	0.031	1.7
Pyroxenite	0.11	28	0.019	5.0
Aggregate	1.60	120	0.41	13.3

All of the above examples indicate low levels of metals at near neutral pH values. This may be due to pyrrhotite being the dominant iron sulfide rather than pyrite. As pyrrhotite is a mono sulfide it does has the same ability to generate the same quantity of acid as pyrite, which is a di-sulfide.

CONCLUSIONS

This study highlighted that including NSR value among the criteria typically used to select samples for ARDML testing allows data to be gathered for an economic spectrum of materials that will likely be removed from an open pit and require management to protect the environment. The use of NSR value also allows material geochemical characteristics to be easily updated as materials are economically classified and reclassified during the course of a project. For the Fedorovo Project this meant that geochemical data was gathered for two open pits, for seven lithologies and for eight NSR value increments.

One of the earliest uses of the resultant Fedorovo geochemical data was the identification of an NSR value ($0/t) that could be used to confidently differentiate between problematic and non-problematic materials, for which there are numerous uses (e.g., road building, tailings dam construction, etc.). Fortunately, at Fedorovo, adequate quantities of non-problematic material were shown to be readily available.

Toward the end of the Fedorovo Project feasibility study, NSR values were also set to differentiate between possible ore, low-grade ore, mid-grade ore and high-grade ore, with all but the latter likely being stored for many years before being processed. Eventually, it would have been possible to characterize each of these materials from a geochemical perspective, predict its likely geochemical behaviour and develop plans for ensuring its appropriate management with respect to protecting the environment.

Over time, as engineering of the Fedorovo Project continues, materials will likely continue to be economically reclassified. However, by having included NSR value in the criteria used to select samples for ARDML testing, it will be possible, if necessary, at any time to easily adjust material geochemical characteristics and environmental protection plans.

This study also highlighted the potential for low level metals leaching in the absence of the acidic conditions. Standard geochemical static ARD prediction methods that assess sulfide reactivity do not adequately address the potential for low level metals leaching and other test methods, such as contact leaching tests and NAG_{metal} assessments, are needed to obtain a complete picture of project geochemical risks.

Finally, it is important to recognize that, typically, low level metal leaching is not problematic. However, when it occurs at a project that is located in both a fisheries area and a headwaters area, as is the case for the Fedorovo Project, the potential for a problem can be greatly exacerbated. Increasingly, this may become the norm in the mining industry and improved methodologies for accurately predicting low level metals leaching, with aggressive water management plans to manage these risks, will likely be required in the future.

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