POLYMET
MINING

NorthMet Project

Geotechnical Data Package
Volume 1 – Flotation Tailings Basin

Version 4

Issue Date: April 12, 2013

List of Attachments

Attachment A	MDNR Geotechnical Work Plan
Attachment B	Oversized Figures and Maps
Attachment C	Material Strength Characterization
Attachment D	Historical Geotechnical Reports
Attachment E	2007 Geotechnical Investigation Laboratory Test Results
Attachment F	2007 Geotechnical Investigation CPTu Sounding Logs and Dissipation Test Results
Attachment G	2007 Geotechnical Investigation Dilatometer Test Results
Attachment H	2007 Geotechnical Investigation SPT Boring Logs
Attachment I	Tailings Mineralogy and Shape Memorandum
Attachment J	NorthMet Tailings Weathering Memorandum
Attachment K	Material Strength Characterization Review by Scott Olson
Attachment L	Processed Test Results
Attachment M	Liquefaction Outputs
Attachment N	NorthMet Probabilistic Seismic Hazard Assessment (PSHA)
Attachment O	CPT Triggering Plots
Attachment P	SEEP/W Output Figures
Attachment Q	SLOPE/W Output Figures

Attachment J

NorthMet Tailings Weathering Memorandum

Technical Memorandum

To: Tom Radue, Bethany Erfourth
From: Tamara Diedrich, Mehgan Blair
Cc: Stephen Day, SRK
Subject: Weathering of NorthMet Flotation Tailings
Date: April 4, 2013
Project: NorthMet Project – 23690862.00-037

Problem Statement

Flotation Tailings produced by a future NorthMet Mine during beneficiation of ore would be comprised of minerals typical of rock from the Duluth Complex (geologic source of NorthMet ore). In geologic time, these minerals can be expected to weather when exposed to surficial conditions, resulting in alteration of the original mineral assemblage through oxidation, hydrolysis, dissolution, leaching, and precipitation of secondary minerals. This process is consistent with the weathering that generally occurs to igneous rock exposed to conditions on the Earth's surface over geologic time.

This memo presents results of a qualitative evaluation of the likely extent of weathering to occur in NorthMet Flotation Tailings over approximately 2,000 years using existing data on mineral, chemical, and physical characteristics of the Flotation Tailings as produced from the NorthMet pilot plant; along with peer-reviewed scientific literature values on weathering rates. Alteration of NorthMet Flotation Tailings due to weathering may, or may not, be consequential with respect to the geotechnical properties of the NorthMet Flotation Tailings; the geotechnical implications of weathering are not addressed in this memo.

Background

Petrographic analysis[1] indicates that NorthMet Flotation Tailings will be comprised of the following minerals:

Table 1. Mineralogy of Flotation Tailings Samples, as Identified by Optical Petrography

Sample ID	P1S	P1SA	P1SOLID	P2S	P3S
Plagioclase (%)	80	75	60	50	60
Olivine (%)	12	15	15	10	10
Clinopyroxene (%)	4	5	5	4	5
Orthopyroxene (%)	1	2	1		1
Pyrite (%)	rare	rare	rare	rare	rare
Pyrrhotite (%)	0.25	0.25	0.25	0.5	0.25
Chalcopyrite (%)	rare	rare	rare	rare	rare
Biotite (%)	1	1	1	1	1
Chlorite (%)	0.5	0.25	1	1.5	1
Serpentine (%)					0.25
Sericite/Muscovite (%)	0.25	0.5	1	2	1
Sphalerite (%)	rare	rare	rare		rare
Galena (%)	rare	rare	rare	rare	rare
Ilmenite (%)	1	1	0.75	1	0.5
Clay/unidentified (%)			15	30	20

Plagioclase (representing 50-80% by volume) makes up the bulk of the tailings. Electron microprobe analysis of selected individual plagioclase crystals in NorthMet ore and waste rock indicates that the plagioclase has an intermediate composition between anorthite (with an idealized formula of $CaAl_2Si_2O_8$) and albite (idealized formula of $NaAlSi_3O_8$). The average NorthMet plagioclase composition is 59% anorthite, and 41% albite (i.e. $An_{59}Ab_{41}$)[2]. This composition of plagioclase is also referred to as labradorite, and has a generalized chemical formula of $Ca_{0.59}Na_{0.61}(Al, Si)_4O_8$.

Plagioclase is susceptible to the primary agents of chemical weathering: water, oxygen, and carbonic acid (produced from the interaction of rainwater with atmospheric CO_2). The

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[1] Tailings Petrographic Description, Appendix B.1 in: SRK Consulting, RS54/RS46- Waste Water Modeling-Tailings NorthMet Project- DRAFT 01, July 20, 2007. Report Prepared for PolyMet Mining Inc.
[2] Results of Microprobe Analysis, Appendix D.3 in SRK Consulting, RS53/RS42- Waste Rock Characteristics/Waste Water Quality Modeling-Waste Rock and Lean Ore- DRAFT 01, March 9, 2007. Report prepared for PolyMet Mining, Inc.

weathering process takes place at the surface of minerals, and results in the *in-situ* formation of new, stable minerals, and leached ions such as silica, potassium, hydrogen, sodium, and calcium in solution, through reaction such as:

$$CaAl_2Si_2O_{8\ (Anorthite)} + H_2CO_3 + H_2O \rightarrow CaCO_{3(Calcite)} + Al_2Si_2O_5(OH)_{4\ (Kaolinite)} \quad (1)$$

Due to the predominance of plagioclase in the NorthMet Flotation Tailings, as well as the likelihood that it will weather to some extent over the timeframe of 2,000 years, the focus of the following evaluation will be on plagioclase weathering.

It is notable, that while making up a small fraction of the volume of the original tailings, iron sulfide minerals (pyrite, pyrrhotite, chalcopyrite, ± sphalerite) and less predominant iron- and magnesium-bearing minerals, such as olivine [$(Mg, Fe)_2SiO_4$] and clinopyroxene [$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$], will also be undergoing weathering. The release of iron, (as Fe^{2+}) from these phases, followed by almost immediate precipitation of iron as Fe^{3+}-oxyhydroxides (in an oxygen-rich system) will result in the accumulation of iron oxide coating on mineral surfaces and cements[3].

Plagioclase Weathering Evaluation

The rate of plagioclase weathering per mass plagioclase at any given time can be represented by:

$$Q = R * S * t \quad (2)$$

Where Q (mol/kg) is the number of moles of plagioclase reacted per kg original plagioclase, S (m^2/kg) is the specific surface area, t (sec) is time, and R (mol $m^{-2}s^{-1}$) is the weathering rate constant for plagioclase.

For the following evaluation of the extent of plagioclase weathering, estimates of S and R were required.

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[3]Iron oxyhydroxide coatings have been shown to increase residual strength, dilatancy and friction angle of sand: Larrahondo, J.M., Zhao, Q., and Burns, S.E., 2010, Effects of ferric oxyhydroxide coatings on sand shear response: a laboratory approach to chemical weathering, *in* Characterization and Behavior of Interfaces: Proceedings of Research Symposium on Characterization and Behavior of Interfaces, 21 September, 2008, Atlanta, Georgia.

Specific Surface Area

In previous investigations[4], Flotation Tailings were separated into particle size fractions representing a fine end member (-200 mesh) and two coarser fractions (+200 to -100 mesh; and +100 mesh). Consistent with equation (2), the extent of weathering will be directly related to the amount of surface area available for reaction. As a simplifying assumption, the Flotation Tailings were assumed to have a size distribution represented by the existing "fine" fraction. This assumption may result in an overestimate of the amount of plagioclase weathered because the fine fraction will have a greater specific surface area than the coarse fraction. In a future NorthMet tailings basin, the actual size distribution of tailings will be intermediate between the fine and coarse fragments and will be dependent at any given location on physics of the depositional environment. Generally, specific surface area is equal to:

$$S = surface\ area/mass \quad (3)$$

Assuming cubic particles with edge length D (m), equation (3) is equivalent to:

$$S = 6D^{-1}\rho^{-1} \quad (4)$$

where ρ (kg/m^3) is the bulk density. Assuming a uniform particle edge length of 0.0375 mm (midpoint of -200 mesh fragment) and an average bulk density[5] of 3,000 kg/m^3, the specific surface area of the fine fraction would be approximately 53 m^2/kg tailings. If 80% of the fine fraction is plagioclase (Table 1), and the plagioclase is uniformly distributed in the tailings (consistent with petrographic observations), this implies that 53 m^2/kg tailings ×0.8 = 42.4 m^2/kg tailings surface area can be attributed to plagioclase.

Weathering Rates

Extrapolating weathering rates over multiple orders of magnitude presents a challenge because weathering rates of silicate minerals are dependent on time due to complex interplay of competing factors[6].

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[4] Laboratory Report for Barr Engineering Company (Tailings Samples), Attachment D, Barr Engineering Company, NorthMet Project Waste Characterization Data Package, Version 10, Issue Date, March 7, 2013.

[5] Laboratory Report for Barr Engineering Company (Tailings Samples), Attachment D, Barr Engineering Company, NorthMet Project Waste Characterization Data Package, Version 10, Issue Date, March 7, 2013.

[6] As described in: White, A. F., and Brantley, S.L., 2003. The effect of time on the weathering of silicate minerals: why do weathering rates differ in the laboratory and field? Chemical Geology, v. 202, p. 479-506, time-dependent silicate weathering rates reflect effect of *intrinsic* factors (having to do with changes in reactive surface area and availability with time) and *extrinsic* factors (changes in the chemical environment with time that decrease energetic driver for dissolution, i.e. thermodynamic systems approaching equilibrium).

Published labradorite weathering rates[7,8] (specific to field-based, geometric surface area-normalized studies) were used to calculate the mass of plagioclase that might be expected to weather over periods of 20, 200, and 2,000 years in NorthMet Flotation Tailings. Table 2 summarizes these calculations.

Table 2. Labradorite weathering rates applied to NorthMet Flotation Tailings.

Weathering Duration (yrs)	Specific surface area (m^2/kg)	Labradorite surface area (m^2/kg tailings)	Log R	Labradorite weathered (mols/kg tailings)	Labradorite weathered (g/kg tailings)	Labradorite weathered (% of original rock, by mass)
20	53	42.4	*-13.7*[1]	*0.001*	*0.14*	*0.0%*
	53	42.4	**-12.9**[2]	**0.003**	**0.91**	**0.1%**
200	53	42.4	*-13.7*	*0.005*	*1.45*	*0.1%*
	53	42.4	**-12.9**	**0.034**	**9.15**	**0.9%**
2000	53	42.4	*-13.7*	*0.053*	*14.50*	*1.4%*
	53	42.4	**-12.9**	**0.337**	**91.47**	**9.1%**

[1] *Italicized* values in Table 1 are from Kenoyer and Bowser, 1992.
[2] **Bold** values in Table 1 are from Benedetti et al., 1994.

Results-Extent of Plagioclase Weathering

The amount of labradorite weathered (as a percent of the original tailings mass) ranges from 0.0-0.1% when weathered for 20 years, from 0.1-0.9% when weathered for 200 years, and from 1.4-9.1% when weathered for 2,000 years.

[7] Kenoyer, G.J., Bowser, C.J., 1992. Groundwater chemical evolution in a sandy silicate aquifer in Northern Wisconsin: 2. Reaction modeling. Water Resources Research, v. 28, p. 591-600.

[8] Benedetti, M.F., Menard, O., Noack, Y., Caralho, A., Nahon, D., 1994. Water-rock interactions in tropical catchments: field rates of weathering and biomass impact. Chemical Geology, v. 188, p. 203-220.