Potential for Acid Mine Drainage in the Duluth Complex Magmatic PGE Deposits

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Background

I am a professional geophysicist and the president of the Center for Science in Public Participation (CSP2). CSP2 is a non-profit corporation based in Bozeman, Montana, which provides technical assistance on mining and water-quality issues to public interest organizations and tribal governments throughout the United States. I received a Mineral Engineering-Physics degree from the Colorado School of Mines in 1969. I received a Master's degree in Geophysics in 1976 and a Ph.D. in Environmental Planning in 1985, both from the University of California at Berkeley. I am a Registered Professional Geophysicist (GP #972) in the State of California. I received my certification in 1991.

I have over 40 years of experience in the field of mineral exploration and development, including 15 years of technical and management experience relating to mining and mineral exploration. For the past 25+ years I have advised public interest organizations and tribal governments on the environmental effects of mining projects, both nationally and internationally. I have provided technical assistance to various entities on proposed, operating, and abandoned mines in 17 states (including Alaska), four Canadian provinces (including British Columbia), Kyrgyzstan, and Northern Ireland. This assistance has included review of underground and open pit mine design, seismic stability for tailings dams, waste rock facilities design, water quality monitoring, water treatment facility design, reclamation planning, and financial assurance for mine closure.

Through my education, research, and work experience I have developed an expertise in assessing the environmental impacts of mining operations with a focus on metal mines and their impacts to surface and groundwater quality. I also have extensive experience in analyzing the occurrence of tailings dam failures, their impacts and cost, and the cost of reclamation and closure sureties for hard-rock mines.

I have been working on issues associated with potential acid mine drainage at Duluth Complex magmatic platinum group element deposits since 2009, when I first reviewed the Draft Environmental Impact Statement for PolyMet's proposed NorthMet mine. Since then I have provided written comments associated with the 2012 Preliminary Supplemental Draft Environmental Impact Statement; the 2013 NorthMet Mining Project and Land Exchange Supplemental Draft Environmental Impact Statement; the 2015 Final Environmental Impact Statement (FEIS) NorthMet Mining Project and Land Exchange; the 2015 Comments on the Geotechnical Stability of the Proposed NorthMet Tailings Basin and Hydrometallurgical Residue Facility in light of the Failure of the Mt Polley Tailings Storage Facility;, and in 2017, Comments on Draft Dam Safety Permit Number 2016-1380, Flotation Tailings Basin.

I have been asked by the Campaign to Save the Boundary Waters to provide a narrative of the story about NorthMet and Dunka, and how they relate to the Twin Metals deposits.

General description of the Duluth Complex magmatic PGE deposits:

The Duluth Complex consists of 12 mafic sub-intrusions emplaced into the older rocks during continental rifting over a 10 to 12 million-year period about 1.1 billion years ago. It covers an area of 6,500 km^2.

Disseminated copper-nickel sulfide mineralization and basal massive sulfide mineralization are presently known to occur in the Duluth Complex. Large resources of low-grade copper-nickel sulfide ore that locally contain anomalous Platinum Group Elements (PGE) concentrations are well documented by drilling in the basal zones of the South Kawishiwi and Partridge River intrusions. The nine deposits that have been delineated occur in the basal 100 to 300 meters of both intrusions (Miller et al. 2002). The mineralization consists predominantly of disseminated sulfides that collectively constitute over 4.4 billion tons of material averaging 0.66 percent copper and 0.2 percent nickel (Listerud and Meineke 1977).

The mineralization consists of 1% to 5% disseminated chalcopyrite ($CuFeS_2$), cubanite ($CuFe_2S_3$), pyrrhotite ($Fe_{(1-x)}S$), and pentlandite ($(\underline{Fe},\underline{Ni})_9S_8$) in a tabular zone parallel to the contact. Better grades of copper, nickel, and PGEs (platinum, palladium, gold, bismuth, tellurium, arsenic) are associated with more mafic units near the top of the mineralized zone (SWRPA 2009).

Types of Mining in the Duluth Complex

Both open pit and underground mining have been discussed as possibilities for mining the disseminated copper-nickel deposits in the Duluth Complex (AMEC 2014). Since the grade of the Duluth Complex deposit minerals are similar, the determination between an open pit and underground mine will probably rely primarily on the proximity of the ore to the surface. Shallower deposits will be mined by open pit methods, and deeper deposits that would require the removal of large amounts of overburden, which would be uneconomic if mined by the open pit method, will be mined by underground mining methods if the economics are favorable.

Metal mining produces a large amount of waste because of the relatively small amounts of desirable metal contained in most deposits. There are two principle types of mine waste produced by mining and milling the ore. Tailings are produced from grinding the ore to silt-sized particles in order to separate metal sulfides from silicate waste minerals. Over 99% of the mined ore will remain as tailings after processing. The second principle source of waste is rock that is mined to either expose the ore, or is mineralized but below ore-grade. For a typical open pit mine the amount of waste rock mined is roughly equal to the amount of ore.

Both tailings and waste rock can be sources of dissolved metal and other ionic contaminants, which affect both surface and ground waters. Geochemical testing is required both of the tailings, and for each separate rock type constituting the waste rock.

Description of the NorthMet deposit:

The NorthMet Deposit is one of the known significant mineral deposits that have been identified within the 30-mile length of the Duluth Complex and just south of the eastern end of the Mesabi Iron Range. The NorthMet Deposit is believed to be the second largest deposit within the Duluth Complex and represents nearly 25 percent of the known mineral resources in the area. (MN DNR 2013)

The assumptions regarding the environmental behavior of the flotation tailings at NorthMet, which probably have similar characteristics to tailings from other Duluth Complex ore bodies, were based on 21 humidity cells (14 for coarse tailings and 7 for fine tailings) generated in the pilot-plant processing tests conducted to refine the metal recovery process. The estimates of tailings effects on water quality at NorthMet are based largely on the results from these humidity cell tests at the point when they had run continuously between 90 and 300 weeks, and can be expected to yield results roughly similar to those from tailings processed at other Duluth Complex ore bodies. (MN DNR 2013)

Results of the humidity cell tests on pilot-plant tailings at NorthMet had sulfate release rates increasing roughly in proportion to total sulfur, and sulfate production declined over time as the sulfide minerals were consumed. The pH of effluent from oxidizing tailings is predicted by modeling to be between 6 and approximately 8.3, though the pH in effluent from tailings with sulfur similar to that of the NorthMet Tailings Basin (sulfur approximately 0.12 percent) is generally above 7. In most samples of tailings subjected to humidity cell testing decreases in pH are associated with increases in the concentrations of some metal cations, such as nickel. Under oxygenated conditions at room temperature, oxidation of the tailings released about 5 mg SO_4 per kg tailings per week, and the range in most tests was between approximately 2 and 8 mg SO_4 per kg tailings per week. (MN DNR 2013)

Results from geochemical laboratory research on waste rock indicates drainage pH values less than 4.5 were produced by Duluth Complex samples with S > 0.41%, and field test piles yielded drainage pH values similar to laboratory values for samples of similar sulfur content. Due to the uncertainty of the drainage quality from rock with sulfur contents near 0.4%, it can only be concluded that critical sulfur content for this Duluth Complex gabbro, below which drainage pH will be above 6.0 and above which drainage pH was less than 6.0, falls in the range of 0.22% to 0.4% sulfur. (White et. al. 2002)

At NorthMet, key environmental characteristics of the waste rock include the following (MN DNR 2013):

Most of the waste rock and pit wall rock would contain some sulfide sulfur, mainly as mineral pyrrhotite ($Fe_{(1-x)}S$), which can produce acid leachate and soluble metals when it oxidizes;

There are essentially no acid-neutralizing carbonate minerals in the waste rock;

Even though some mafic silicate minerals could neutralize acid, metalloids like arsenic, selenium, thallium, and antimony, could be liberated if present;

Sulfide-bearing rock from the NorthMet Project may oxidize for several years before producing acidic leachate;

The rate of sulfide mineral oxidation in excavated NorthMet waste rock would be approximately proportional to the total sulfur content of the material, and the rate could increase several fold if the pore water were to become acidic; and,

If the pore-water pH were to shift from neutral to acidic, then the rate of sulfide mineral oxidation and associated release of some metal cations (e.g., nickel and copper) would increase dramatically. (MN DNR 2013)

The mechanism most responsible for the release of contaminants from waste rock and tailings is oxidation of sulfide minerals, primarily pyrrhotite ($Fe_{(1-x)}S$). The sulfide-oxidation reaction produces sulfuric acid, and releases soluble metals (e.g., cobalt, copper, iron, and nickel) that is bound in sulfide minerals. At the NorthMet deposit, a Duluth Complex sulfide copper deposit that has been studied in detail, secondary effects include leaching of some metals (primarily nickel and chromium) from silicate minerals, particularly where acidic pore waters increase silicate solubility. (MN DNR 2013)

Mine-related blasting and excavation dramatically increases the surface area and porosity of the rock, which allows rapid introduction of atmospheric oxygen and flushing of solutes by water. Within the pit walls and underground workings, the blasting effects increase the surface area available for oxidation for approximately 50 feet surrounding the blast holes (Kempton et al. 2010). Water that comes into contact with pit walls and underground workings, especially after mine closure, can be expected to be contaminated.

An issue with waste storage in the Duluth Complex is that the terrain is relatively flat and it is difficult to find large areas where bedrock is shallow or exposed. Groundwater flow is more complicated and less restricted in both depth and area in comparison to a site located in the mountains. Containing and/or collecting groundwater is more difficult and expensive as the terrain flattens out. In the case of the NorthMet Project, the proposal is to construct impermeable slurry walls from the surface down to bedrock to restrict the flow of contaminants from waste rock and tailings to outside surface and ground waters.

This is theoretically possible, but is dependent on a good “seal” with the underlying bedrock, as well as bedrock that is not too fractured in its upper portion to provide a path for groundwater to go under the slurry wall.

Description of the Dunka deposit;

The Dunka Mine is a large, open-pit taconite mine located in northern Minnesota at the eastern end of the Biwabik Iron Formation. The mine covers approximately 400 acres and has a depth of around 325 feet. It sits along the western edge of a small watershed (2300 acres), which is drained by a small stream called Unnamed Creek. During 30 years of operation, over 50 million metric tonnes of sulfide-containing waste was removed and stockpiled. (Eger 2010, pp. 4-5) The waste is overburden to the Biwabik iron ore, and comes from the Duluth Complex formation. The Duluth Complex contains disseminated metal sulfides that are proven to lead to acid generation.

There are five waste rock piles at the Dunka site. These waste piles have all been reclaimed with soil, clay, and/or synthetic covers in some combination (Eger 2010, Table 2-1). All of this waste is now producing acidic drainage. The purpose of the covers is to limit the amount of contamination that must be collected and treated. Infiltration can be limited with these covers, but cannot be completely stopped.

The seepage from each waste pile is collected and treated in five constructed wetlands. Passive wetland treatment will typically remove metals if enough residence time is provided for the chemical and physical removal processes to work, but wetlands will do little to remove sulfate from the contaminated waters. At the Dunka wetland complex there was insufficient area to construct two of these wetlands – at Seep 1 and EM8 the wetlands are only about half of the size calculated to provide proper treatment (Eger 2010, p. 13). Although there are other factors that will also control the effectiveness of the wetland treatment system, at a minimum an undersized system will lose its effectiveness earlier than a properly sized wetland.

Most of the seeps drain into Unnamed Creek, which flows into Bob Bay. The Dunka Pit is now full of water, and it overflows into the Dunka River to the south of the pit.

Water quality at the seeps is monitored by the Minnesota Pollution Control Agency. Copper is a metal that is toxic to fish and other aquatic organisms at very low levels. The copper levels in the discharges from the treatment wetlands are generally below chronic toxicity levels at seeps W-2/3D, W-1D, and Mine Pit Dewatering Discharge - South #1. However, at Seep X, copper is acutely toxic annually from Dec-Apr, the winter period when flow from a seep is typically low. Seep X appears to have year-round flow, which diminishes in the winter. Copper levels are at chronic toxicity levels at Seep 1, which generally flows from Apr-Nov. (MPCA 2017)

All of the seeps have sulfate levels that are significantly elevated due to the decomposition of the sulfide minerals in the waste rock. Mine Pit Dewatering Discharge - South #1 has been monitored for copper, but not for sulfate. Sulfate is not listed as a primary contaminant by the USEPA, but its relationship to toxicity is of concern in waters where wild rice grows, and it is potentially directly toxic to other aquatic organisms EPA has suggested that “the salt mixture dominated by salts of SO_4^{-2} and HCO_3^{-1} is believed to be an insurmountable physiological challenge for some species.” (USEPA 2011). Sulfate levels in the seep discharges are approximately 1000-1500 mg/L spring-fall. Sulfate levels at Seep X are somewhat higher.

Recent studies have documented potential impact levels on wild rice and other aquatic organisms. Mybro et al. (2017) have noted that an analysis of an extensive suite of physical and chemical parameters from 108 different sites with potential wild rice habitat shows that pore water sulfide toxicity is a primary biogeochemical factor controlling the occurrence of wild rice populations in otherwise favorable habitat. The median sulfate concentration in these lakes was 10 mg/L. Similarly, Pollman et al (2017) determined that although their modeling showed that both sediment total oxygen content and sediment iron are important contributors to the toxic impacts of sulfide, regulating sulfate is the only viable mechanism to protect wild rice against sulfide toxicity.

There is also some research addressing the potential impacts of cumulative ionic toxicity to invertebrates. In 2015, Johnson & Johnson noted that the discharge of specific conductance above the level of 300 µS/cm, established as guidance for Appalachian streams, is highly likely to result in extirpation of 5% or more of invertebrate genera in Minnesota's Boundary Lakes & Hills and the northern Toimi Drumlins ecoregions. The assumptions and data used from both Appalachia and Minnesota by Johnson & Johnson were reviewed and confirmed by the USEPA (2016).

I have reviewed water quality data collected by the Minnesota Pollution Control Agency at five wetland discharge points that treat seeps from waste rock, and from the pit overflow discharge, at the Dunka mine from 2000 through 2015. I have made the following observations:

Seep W-2/3D (061) Wetland Treatment Discharge: Sulfate levels in the discharge are approximately 1,500 mg/L during the winter (low flow), and approximately 750 mg/L during the summer. The Minnesota water quality discharge standard for sulfate is 10 mg/L. This discharge goes into Bob Bay of Birch Lake.

Seep W-1D (051) Wetland Treatment Discharge: Sulfate levels in the discharge are approximately 1,000 mg/L during winter low-flow, and approximately 750 mg/L during the summer. The level of nickel in the discharge exceeds the surface water hardness-based water quality standard of 169 ug/L in December thru January in most of the years of monitoring. This discharge goes into Unnamed Creek.

Seep 1 (043) Wetland Treatment Discharge: Sulfate levels in the discharge are approximately 1,000 mg/L during the winter, and approximately 750 mg/L during the summer. The level of nickel in the discharge is approximately 4,000 ug/L in the winter, and 2,000 ug/L in the summer. Zinc exceeded the hardness-based water quality standard of 393 ug/L from 2000 through 2008. Since 2009, the level of zinc has decreased to approximately 100 ug/L, but no data has been collected from December through February, when the zinc level would be expected to be highest. This discharge goes into Unnamed Creek.

Seep X (044) Wetland Treatment Discharge: Sulfate levels in the discharge are approximately 1,750 mg/L year round. The level of nickel in the discharge is approximately 500 ug/L, and exceeds the hardness-based water quality standard of almost all measurements. Copper exceeded the hardness-based water quality standard in December through March from 2000 to 2010. From 2010 through 2015 the level of copper in the discharge is approximately 20 ug/L (32 ug/L is the water quality standard). This discharge goes into Unnamed Creek.

Seep EM-8 (041) Wetland Treatment Discharge: Sulfate levels in the discharge are approximately 1,500 mg/L during the winter, and approximately 1,000 mg/L during the summer. The level of nickel in the discharge is approximately 2,000 ug/L in the winter, and 750 ug/L in the summer. The surface water hardness-based water quality standard is 169 ug/L. This discharge goes into Unnamed Creek.

Mine Pit Dewatering Discharge - South #1: There is no sulfate data being collected at this discharge. Since sulfate is the primary pollutant of concern in these discharges, this is a significant omission, especially since the discharge is directly into the Dunka River.

In summary, the levels of sulfate discharged from the waste rock at Dunka are two orders of magnitude greater than level of background sulfate in most of the lakes and streams in this area. Although determining the level of toxicity to wild rice is a complex function of several variables, including sulfate, the level of sulfate is the only variable that can be controlled (Polleman et al. 2017). The existing water quality standard for sulfate of 10 mg/L was set to protect wild rice.

The passive water treatment systems are not meeting water quality standards for nickel at Seep 1, Seep X, and Seep EM-8. The water quality standard for zinc is probably being exceeded at Seep 1, but there is no data to either confirm or deny this.

Sulfate data is not being collected at the discharge from the Dunka pit into the Dunka River.

Comparison to the Birch Lake deposits:

The Birch Lake deposit lies approximately one mile northeast of the Dunka mine pit. The Maturi, Maturi Southwest and Spruce Road deposits all lie within a 10-mile distance northeast of the Birch Lake deposit. The NorthMet deposit lies 6 miles southwest of the Dunka mine. The Maturi, Maturi Southwest, Birch Lake, and Spruce Road deposits, the Dunka mine, and the NorthMet deposit, all lie along a 20-mile long northeast-southwest trending line.

Mineralization at the Maturi, Maturi Southwest, Birch Lake, and Spruce Road deposits is hosted in the Duluth Complex. The basal portion of the South Kawishiwi intrusion hosts all four deposits. Mineralization primarily comprises chalcopyrite, cubanite, pentlandite, pyrrhotite, and talnakhite ($Cu_9(Fe, Ni)_8S_{16}$) with numerous base and precious metals-bearing trace minerals. These minerals are disseminated within the basal mineralized zone. (AMEC 2014)

The Maturi and Maturi Southwest deposits consist of a tabular sheet of disseminated copper-nickel-iron sulfide mineralization 5 feet to 865 feet thick (average 215 feet) in the basal mineralized zone, which rests on or close to the South Kawishiwi–granite contact. The geology at Birch Lake is similar to Maturi but distinct because the basal mineralized zone of the South Kawishiwi intrusion in this area includes numerous ultramafic and oxide (magnetite/ilmenite/chromite) layers that are not present at Maturi or Maturi Southwest. Relative to Maturi and Maturi Southwest, Birch Lake contains significantly more ultramafic intrusive rocks. Troctolitic rocks comprise much of the South Kawishiwi intrusion at Spruce Road and carry abundant rafted basement inclusions of sedimentary hornfels, basaltic hornfels, anorthosite and iron formation. In contrast to the Maturi and Birch Lake deposits, there does not appear to be any specific correlation of mineralization to lithology and there is no key unit or hanging wall marker horizon, such as the pegmatitic unit that overlies the mineralized unit at Maturi. (AMEC 2014)

The mineralization of the Maturi, Maturi Southwest, Birch Lake, and Spruce Road deposits, which contain sulfides at higher concentrations than the NorthMet deposit or Dunka mine waste rock, could be expected to produce the same contaminants as at Dunka, but at higher rates and concentrations due to the higher amounts of sulfide mineralization and lower pH this waste will likely yield.

Like Dunka, at all of the sulfide mine developments in the Duluth Complex it is extremely likely there will seepage from waste rock, pit walls, and tailings to ground and/or surface waters that will require treatment for elevated levels of metals, and potentially sulfate. Sulfate levels of the discharges from conventional and passive water treatment systems will not reduce the sulfate contaminant levels, which will be two or more order of magnitudes higher than the Minnesota water quality standard for sulfate of 10 mg/L.

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