**REPORT – Revision 0A**

# Twin Metals Minnesota Project

*Acid Rock Drainage White Paper*

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# Distribution List

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# Executive Summary

This paper presents an overview of potential geochemical environmental issues associated with a proposed non-ferrous underground mine for copper (Cu), nickel (Ni), cobalt (Co) and platinum group elements (PGEs). The proposed Twin Metals Minnesota Project (TMM Project) targets the Maturi Deposit within the Duluth Complex in northeast Minnesota near Ely. The potential geochemical environmental issue of most concern for non-ferrous mining is the generation of acid rock drainage (ARD) and associated metal leaching (ML), commonly combined using the acronym ARD/ML. The process of ARD generation is very well understood, as are the engineering options available to prevent, minimize, and mitigate ARD formation. Based on all geochemical information generated to date, the long-term potential for ARD generation for the TMM Project is considered low to non-existent.

**Acid Rock Drainage and Metal Leaching - State-of-Practice**

Research into the process of ARD formation and methods to minimize its impacts has been conducted worldwide for more than 50 years. Much progress has been made in the last 20 years through a number of research organizations, government agencies and industry consortiums. The Global Acid Rock Drainage Guide (GARD Guide), which is sponsored by the International Network for Acid Prevention (INAP), consolidates state-of-practice information on the prediction, prevention and management of ARD. The GARD Guide represents a collaborative effort by many experts in the field of ARD. Specific contributors and advisors to the GARD Guide include representatives from the mining industry (including TMM), academia, private consulting, and government agencies from around the world. The widespread and global use and referencing of the guide are an indication of its acceptance and credibility.

ARD is formed by the natural oxidation of sulfide minerals when exposed to air and water. In general, the ARD risk associated with an ore deposit is proportional to the amount of sulfides present and inversely proportional to the amount of neutralization potential available. For the same deposit type, sulfide mineralogy and concentrations, and thus ARD potential, can be highly variable. Therefore, it is important to assess, design and plan mining projects on a site-by-site basis.

**Northeast Minnesota's Duluth Complex Mineral Deposit**

The Maturi Deposit, located within the larger Duluth Complex in northeast Minnesota, is a magmatic sulfide deposit. It is one of the world's largest undeveloped copper-nickel deposits. Unlike many other types of ore deposits, the sulfide minerals in these deposits are directly associated with and generally restricted to the ore, thereby limiting the potential for the generation of potentially acid generating (PAG) waste materials.

Considerable information is available regarding the environmental behavior of the Duluth Complex. Studies of the ARD potential of Duluth Complex rocks have been conducted at the laboratory and field scale by U.S. government research organizations and private industry. The information available from these studies provides a fundamental understanding of the expected environmental behavior of the materials originating from the TMM Project. To add to this understanding, TMM has implemented a comprehensive Mine Material Characterization Program (MMCP) aimed at determining the geochemical behavior of Project-specific mine materials, including waste rock, ore, and tailings. This program has been developed in cooperation with the Minnesota Department of Natural Resources (MDNR). TMM's commitment to comprehensive characterization of the geochemical behavior of the Maturi Deposit began during exploration drilling and continues today, for a total duration of almost one decade.

The ARD potential of mine materials is determined by the balance between the acid generation potential (AP) of a material (i.e. sulfide concentration) and the neutralization potential (NP). The sources of AP and NP in Duluth Complex rock are well understood.

Geochemical characterization of Duluth Complex rocks by TMM and others has indicated that total sulfur content and sulfide mineralogy are the controlling factors in the rate and severity of ARD generation. Sulfide mineralization within the Maturi Deposit comprises copper, nickel and iron sulfides. Iron sulfides (e.g., pyrite and pyrrhotite) typically are the most common source of ARD due to their high reactivity, but their abundance in the Maturi Deposit is lower than the copper and nickel sulfides. The copper sulfide chalcopyrite, the most abundant sulfide mineral in the Maturi Deposit, oxidizes at a slower rate than the iron sulfides and may not generate acid upon oxidation. As such, the potential for ARD generation of the Maturi Deposit due to sulfide oxidation is much lower than many other types of deposits containing sulfide minerals.

Silicate minerals are the primary source of NP in Duluth Complex rocks. Silicate mineral NP is sufficient to maintain circum-neutral pH conditions for extended periods for rock with a low total sulfur content. For material with higher total sulfur contents, silicate NP is responsible for a delay in the development of acidic conditions, thereby allowing time for implementation of appropriate engineering controls. The lag time to ARD is also related to sulfur content (i.e. lag time decreases as sulfur content increases).

TMM's characterization program includes both short-term and long-term testing (i.e. static and kinetic tests, respectively). In addition to the evaluation of ARD potential, the testing program provides information to evaluate sulfate and metal leaching from mine materials. These data support the development of mine water quality estimates, a multi-disciplinary effort which includes consideration of many other factors (e.g., water balance, physical characteristics of potential source materials, baseline water quality, geochemical conditions in the receiving environment, etc.).

A comprehensive understanding of the geochemical behavior of mine materials is fundamental to the prediction and prevention of possible impacts to the receiving environment. The extensive geochemical dataset and deep understanding of the behavior of Duluth Complex rocks result in confidence in the prediction of potential environmental impacts and selection of effective engineering controls.

**Twin Metals Minnesota Project Design**

Prevention of ARD/ML starts at exploration and continues throughout the mine-life cycle. The GARD Guide presents methods for prevention of ARD/ML throughout the mine-life cycle, many of which have been incorporated into the TMM Project design. TMM's strategy to mine material management focuses first on elimination of ARD/ML risk, with engineering controls as a secondary or complementary action. Key aspects of TMM's waste management plan include minimizing the mass, sulfur content and exposure of any sulfidic material mined and brought to surface. The environmentally focused mine design has eliminated the features which are most often the cause of long-term ARD/ML issues at other mine sites:

- **No Open Pit**: Resource development would be by underground mining as opposed to open pit. The environmental benefits of underground mining, as compared to an open pit, include reduced land disturbance and waste generation and the avoidance of a pit lake or other large surface feature at closure.
- **No Waste Rock Stockpiles**: During operations, all waste rock would remain underground as backfill. The Project would not generate any permanent or even long-term surface stockpiles.

- **No High-Sulfur Tailings:** By design, because virtually all of the sulfide minerals are removed in the concentration process, the sulfur content of the tailings would be low (≤0.2%), which is below the threshold identified for acid generation. Storage in a dry stack facility, as opposed to a traditional slurry impoundment, is current industry best practice.

The proposed engineered environment contains the following features:

- Surface:
  - **Tailings:** The sulfur content of the tailings is very low as virtually all sulfur reports to the concentrates. As such, the tailings are classified as having a low to non-existent potential to generate ARD. Approximately 60%of the tailings would be dewatered and compacted in a dry stack facility which would be lined, covered, and progressively reclaimed with native soil and vegetation as the project progresses. In addition to the very low sulfur content, tailings management, which includes compaction and progressive reclamation, limits exposure of the tailings to air and water. Use of a dry stack reduces ground disturbance relative to traditional slurry impoundments, eliminates the need for water-retaining structures such as dams, and significantly diminishes draindown from the tailings mass relative to a tailings slurry.
  - **Waste Rock**: During construction and the first two years of operations, there would be minimal and temporary storage of waste rock and ore on the surface in a lined facility (approximately one million tonnes for less than four years). This duration is less than the anticipated lag time to acid generation for most waste rock that is generated during the early years of operation. During the short period of storage on surface, all contact water would be captured. All waste rock on surface would be processed though the concentrator within the first two years of operations. Therefore, there would be no long-term storage of waste rock on surface.
  - **Ore:** Covered stockpiles would be used to temporarily store ore on the surface during operations. The duration of ore storage on surface would be very short (i.e. days) prior to processing.
  - **Water Management**: All surficial contact water would be captured to prevent its discharge to the environment.
- Underground:
  - Sulfide mineralization would be exposed underground. Stopes would typically be backfilled within a one-year timeframe.
  - During operation, underground water would be collected and used in the process.
  - Waste rock would remain underground during operation and there would be no surficial waste rock facilities after closure.
  - All waste rock, with the exception of the waste rock brought to surface during the construction period, and a portion of the tailings (approximately 40%) would be used for underground backfill. Binder would be added for geotechnical purposes, but would also represent a source of additional alkalinity and buffering. Waste rock backfilled in the stopes would be encapsulated in cemented tailings, thereby minimizing exposure of any sulfidic rock to oxygen.

  - Flooding of the underground mine following cessation of mining activities would virtually eliminate sulfide oxidation.

- The modern regulatory environment requires more than a hundred local, state and federal environmental permits to plan, construct, operate, and close the proposed underground mine. This high level of scrutiny ensures the use of proven, state-of-the-art practices.

The project-specific details presented in this paper are preliminary and consist of project information that has been developed as part of overall project evaluation and engineering as presented in the Mine Plan of Operations (MPO; TMM 2021b).

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**FIGURES**

# List of Acronyms and Abbreviations

| | |
|---|---|
| ADTI | Acid Drainage Technology Initiative |
| AGT or Main AGT | augite-bearing troctolite |
| AN-Series or ANS | anorthositic series |
| AP | acid generation potential |
| ARD | acid rock drainage |
| ASTM | American Society of Testing Materials |
| BMZ | basal mineralized zone |
| CAFTA | Central American Free Trade Act |
| CNAMD | Chinese Network for Acid and Metalliferous Drainage |
| EIA | Environmental Impact Assessment |
| EIS | Environmental Impact Statement |
| GARD Guide | Global Acid Rock Drainage Guide |
| GRB | Giants Range Batholith |
| HCT | humidity cell test |
| INAD | Indonesian Network for Acid Drainage |
| INAP | International Network for Acid Prevention |
| LLR | longitudinal longhole retreat |
| MDNR | Minnesota Department of Natural Resources |
| MEND | Mine Environmental Neutral Drainage Program |
| ML | metal leaching |
| MMCP | Mine Material Characterization Program |
| MPO | Mine Plan of Operations |
| NAG | net acid generation |
| NGOs | non-governmental organizations |
| NMD | neutral mine drainage |
| NP | neutralization potential |
| NPAG | non-potentially acid generating |
| NPL | National Priorities (Superfund) List |
| NPR | net potential ratio |
| PADRE | Partnership for Acid Drainage Remediation in Europe |
| PAG | potentially acid generating |
| PEG | pegmatoidal |
| PGEs | platinum group elements |
| SANAP | South American Network for Acid Prevention |
| SKI | South Kawishiwi Intrusion |
| SMIKTR | Sustainable Minerals Institute–Knowledge Transfer |
| TC | total carbon |
| TIC | total inorganic carbon |
| TMM | Twin Metals Minnesota |
| USEPA | United States Environmental Protection Agency |
| WRC | Water Research Commission |
| XRD | x-ray diffraction |
| XRF | x-ray fluorescence |

# 1.0 INTRODUCTION

This paper presents and discusses potential geochemical environmental issues associated with the proposed Twin Metals Minnesota Project (TMM Project), a world-class underground Copper-Nickel-Cobalt-Platinum Group Elements (Cu-Ni-Co-PGE) mine in northeast Minnesota near Ely. The proposed non-ferrous underground Cu-Ni-Co-PGE mine targets the Maturi Deposit of the Duluth Complex. The project-specific details presented in this paper consist of project information that has been developed as part of overall project evaluation and engineering as presented in the Mine Plan of Operations (MPO; TMM 2021b). The mine design presented in the MPO represents the culmination of over ten years of engineering and environmental studies.

**Acid Rock Drainage and Metal Leaching – Problem Definition**

A potential geochemical environmental issue for mining projects is the generation of acid rock drainage (ARD) and associated metal leaching (ML), commonly combined using the acronym ARD/ML. ARD is formed by the natural oxidation of sulfide minerals when exposed to air and water. In general, the ARD risk associated with an ore deposit is proportional to the amount of sulfides present and inversely proportional to the amount of neutralization potential available. Because the mobility of many metals increases as pH decreases, an increase in metal leaching occurs in association with ARD formation. For the same deposit type, sulfide mineralogy and concentrations, and thus ARD potential, can be highly variable. The project setting (e.g., climate) and methods of resource development and waste management also affect ARD potential. Therefore, it is important to assess, design and plan mining projects on a site-by-site basis.

**Acid Rock Drainage and Metal Leaching – State-of-Practice**

A focus on the evaluation of ARD/ML potential is not unique to the TMM Project; ARD/ML is the number one environmental issue facing the global hard rock metal mining industry (e.g., INAP 2014). Because of the industry-wide nature of the issue, research into the process of ARD formation and methods to minimize its impacts has been conducted for over 50 years. Much progress has been made in the last 20 years through a number of research organizations and consortiums. The International Network for Acid Prevention (INAP), of which Twin Metals Minnesota is a member, has consolidated the available information and produced a Global Acid Rock Drainage Guide (GARD Guide) that is up-to-date and global in scope (INAP 2014).

INAP's goal was to produce a guide that would be a key reference for the mining industry, regulators, non-governmental organizations (NGO's) and the public on the subject. To this end, the GARD Guide summarizes the best technical and management practices with the objective of creating a body of work with high industry and external stakeholder credibility. The guide assists the industry in providing high levels of environmental protection, assists governments in the assessment and regulation of affairs under their jurisdiction, and enables the public to have a higher degree of confidence in and understanding of acid prevention plans and practices. Overall, the GARD Guide provides a structured and standardized system to identify and catalogue proven techniques for characterization, prediction, monitoring, treatment, prevention and management of ARD (as well as neutral mine drainage [NMD] and saline drainage [SD]).

The GARD Guide represents a collaborative effort by many experts in the field of ARD. The guide was funded by INAP and the Mining Association of Canada (MAC). It was developed in partnership with the Global Alliance, whose member organizations collectively represent significant technical expertise on ARD/ML prevention, mitigation and mine waste management. Global Alliance member organizations include the Sustainable Minerals Institute–Knowledge Transfer (SMIKTR - Australia), the Mine Environmental Neutral Drainage Program (MEND - Canada), the Chinese Network for Acid and Metalliferous Drainage (CNAMD), the Partnership for Acid Drainage

Remediation in Europe (PADRE), the Indonesian Network for Acid Drainage (INAD), the Water Research Commission (WRC - South Africa), the South American Network for Acid Prevention (SANAP), and the Acid Drainage Technology Initiative (ADTI - United States of America). Specific contributors and advisors to the GARD Guide included representatives from the mining industry, academia, private consulting, and government agencies (e.g., the United States Bureau of Land Management) from around the world. Use and reference of the guide is an indication of its acceptance and credibility. For example, the United States Environmental Protection Agency (USEPA) appended the Executive Summary of the GARD Guide to a document prepared by the Central American Free Trade Act (CAFTA) on Environmental Impact Assessment (EIA) technical review guidelines for mining (CAFTA DR and US Country EIA and Mining Experts 2011; Chatwin 2015).

As demonstrated in the GARD Guide, proper characterization of mine materials, drainage-quality prediction, and mine-waste management can prevent ARD formation in most cases and minimize ARD formation in all cases. Activities to prevent, minimize and / or manage ARD/ML must commence at exploration and continue throughout the mine life cycle. Ongoing ARD/ML planning and management are critical to the successful prevention of ARD/ML.

The management of ARD/ML continues to undergo improvements, in part in response to increased regulatory oversight, as referenced in the literature:

- *"Best practices in AML [abandoned mine land] reclamation are continuously being tested and **proven** by the BLM, other Federal agencies. States, contractors, and mining companies."* (BLM and USFS 2007).
- *"Experience gained by the Forest Service and others during the past few decades has demonstrated that there are no quick and easy solutions to abandoned mine lands and water protection. However, modern mining regulations and progress made using collaborative partnerships and a watershed approach point positively to the potential for solid success."* (USDA Forest Service 2005)
- *"The rapid evolution of modern mining technologies and best management practices has also reduced both the "degree and duration of risk" for the release of hazardous substances to **de minimus levels**. Since the 1990s, both the Bureau of Land Management and the U.S. Forest Service have reported that thousands of mine plan operations have received approval, and not one has been added to the National Priorities (Superfund) List (NPL), demonstrating the success of existing, comprehensive regulatory programs."* (Sanderson 2017).

**Acid Rock Drainage and Metal Leaching – TMM Project**

A site-specific evaluation must be conducted to evaluate the ARD/ML potential of a project. While deposit geology is a primary factor in the determination of ARD/ML potential, the project setting, method of resource development and waste management practices are equally important in the assessment of ARD/ML. As shown in Figure 1, characterization of the mine material and receiving environment is conducted to identify potential ARD/ML sources and pathways to the receiving environment and to define if ARD/ML is a potential concern. If an ARD/ML concern is identified, mine design, which includes decisions regarding the method of resource development and engineering controls, takes into account prevention and/or mitigation of ARD/ML.

For over a decade, TMM has conducted mine material and receiving environment characterization studies to understand the ARD/ML potential of their project. TMM's strategy to mine design and mine material management focuses first on elimination of ARD/ML risk, with engineering controls as a secondary or complementary action. The GARD Guide presents methods for prevention of ARD/ML throughout the mine-life cycle, many of which have been incorporated into the TMM Project design. Key aspects of TMM's waste management plan include minimizing the mass, sulfur content and exposure of any sulfidic material mined and brought to surface. The environmentally focused mine design has eliminated the following features that are most often the cause of long-term ARD/ML issues at other mine sites:

- **No Open Pit**: Resource development would be by underground mining as opposed to open pit. The environmental benefits of underground mining, as compared to an open pit, include reduced land disturbance and waste generation and the avoidance of a pit lake or other large surface feature at closure.
- **No Waste Rock Stockpiles**: During operations, all waste rock would remain underground as backfill. The Project would not generate any permanent or even long-term surface stockpiles.
- **No High-Sulfur Tailings:** By design, because virtually all of the sulfide minerals are removed in the concentrating process, the sulfur content of the tailings would be low (≤0.2%), which is below the threshold identified for acid generation. Storage in a dry stack facility, as opposed to a traditional slurry impoundment, is current industry best practice.

TMM's approach to ARD/ML prevention/mitigation includes the following:

- **ARD/ML Understanding**: Investment in site-specific characterization studies to understand ARD/ML potential.
- **ARD/ML Prevention and Mitigation**: When a potential ARD/ML risk is identified, adoption of state-of-the-art mine design to eliminate and/or mitigate ARD/ML issues.

Following an introduction to the TMM project (Section 2), this paper summarizes the extensive geochemical testing programs that have been conducted to understand the ARD/ML potential of mine materials (Section 3) followed by the aspects of mine design focused on ARD/ML prevention/mitigation (Section 4).

# 2.0 TWIN METALS MINNESOTA PROJECT OVERVIEW

The polymetallic deposits of the Duluth Complex, including the TMM Project, are so-called magmatic sulfide deposits, formed by the segregation and crystallization of sulfide- and metal-rich immiscible liquids from crystallizing mafic magmas (Plumlee et al. 1999). Once formed, the droplets of sulfide liquid settle through less dense magma. The sulfide liquid acts as a "collector" for copper, nickel, cobalt and PGEs because these elements prefer the sulfide liquid to the magma by a factor of 10 to 100,000 times. Unlike many other types of ore deposits, the sulfide mineralization of these deposits is therefore directly associated with the ore, thereby limiting the potential for the generation of potentially acid generating (PAG) waste materials.

The proposed Project is an underground mine that targets the Maturi mineral deposit, located approximately nine miles southeast of the city of Ely, Minnesota. TMM has conducted numerous studies (many ongoing) to characterize both the deposit and the surrounding environment to inform decisions on the development of this resource with environmental stewardship.

TMM would adopt modern mining methods to appropriately manage mine materials (i.e. tailings, waste rock and ore) focusing on prevention of ARD generation and the release of metals and/or sulfate to the environment. The mine design and material management presented in the MPO (TMM 2021b) take into account research by others and extensive geochemical characterization of Maturi ore and mine wastes conducted by TMM.

The United States is a world-leader in the implementation and enforcement of legislation to protect the environment. More than one hundred local, state and federal environmental permits will be required to plan, construct and operate the proposed underground mine. TMM’s license to operate is, therefore, dependent on development of the resource in an environmentally responsible manner.

## 2.1 Deposit Geology

Magmatic sulfide deposits are formed by the segregation and crystallization of sulfide- and metal-rich immiscible liquids from crystallizing mafic magmas (Plumlee et al. 1999). Once formed, the droplets of sulfide liquid settle through less dense magma. The sulfide liquid acts as a "collector" for copper, nickel, cobalt and PGEs because these elements prefer the sulfide liquid to the magma by a factor of 10 to 100,000 times. These deposits are characterized by lenses or bodies of sulfides.

The South Kawishiwi Intrusion (SKI) of the Duluth Complex, which hosts the Maturi Deposit, is categorized as a layered mafic intrusion. Figure 2 shows an example cross-section through the Maturi Deposit. Eight major units are defined in the Project geologic model (Table 1).

- **Ore Zone**: The basal mineralized zone (BMZ) is the unit which hosts the mineralization (lowermost unit of South Kawishiwi Intrusion - SKI). The thickness of the BMZ is variable, ranging from tens of feet (a few meters) to over 350 feet (~100 meters) and averaging about 200 feet (~60 meters) (TMM 2021a). The BMZ mineralization includes both base metals (Cu, Ni and Co) and precious metals (palladium [Pd], platinum [Pt], gold [Au] and silver [Ag]). The top of the BMZ outcrops at the surface in certain areas and extends to depths of at least approximately 4,900 feet (1,500 meters). TMM would mine ore between depths of approximately 400 feet (120 meters) and 4,000 feet (1,200 meters).
- **Hanging Wall and Footwall**: The hanging wall and footwall refer to the geologic units immediately above and below the ore zone, respectively. The hanging wall rock to the BMZ includes the pegmatoidal unit (PEG), augite-bearing troctolite (Main AGT or AGT), and the anorthositic series (AN-Series or ANS), with PEG being the most prevalent hanging wall unit. The Giants Range Batholith (GRB) represents the footwall

of the deposit. The underground mine would be accessed via a decline constructed through the hanging wall. Much of the underground mine infrastructure would be constructed in the footwall.

With the exception of the GRB, the non-mineralized units of the Project have similar and consistent chemical and mineralogical compositions. The principal compositional variation is in the proportions of plagioclase, olivine and clinopyroxene, indicating a very comparable environmental behavior when extracted during mining. Outside of the BMZ, sulfide mineralization rarely occurs in the hanging wall and is generally restricted to the top 30 feet of the footwall.

## 2.2 Twin Metals Minnesota – Resource Development

The TMM Project is a proposed underground mine. The Maturi Deposit would be mined using a longitudinal longhole retreat (LLR) mining method with backfill over a 25-year period. An approximately 3-year construction period would precede mining.

Stope development would begin at a depth of approximately 400 feet (~120 meters) and extend to a depth of approximately 4,000 feet (1,200 meters) below the ground surface. The LLR mining method would target only those portions of the deposit considered ore, thereby eliminating the need for above-ground waste rock stockpiles. Additionally, the underground mine would include a minimum 400-feet wide (~120-meter) crown pillar from ground surface to prevent subsidence.

Some project details relevant to mine material management are as follows (TMM 2021b):

- **Ore**: Ore would be crushed underground and transported to surface for temporary storage in either the primary or secondary ore stockpile prior to milling. The primary stockpile would be a covered facility with a concrete floor. The facility would have a 3-day storage capacity. The secondary ore stockpile, a lined facility, would have a capacity of 2.5 days and would be used intermittently throughout mine operation. The sulfide mineral content of the ore is expected to range from approximately 1 to 5 wt.%.
- **Processing**: Processing would produce copper, nickel and PGE concentrates. Virtually all of the sulfur present in the ore would report to the concentrates.
- **Tailings**: Processing would also produce low-sulfur (≤0.2 wt.%), non-acid generating (NPAG) tailings. Tailings would be thickened to 65 to 70% solids in a conventional thickener and stored in two fashions.
  - **Surface Storage**: Approximately 60% of the tailings would be dewatered to produce a filter cake in the target range of 84% to 87% solids. This material would be transported to and compacted in a dry stack facility which would be lined, covered, and progressively reclaimed with native soil and vegetation as the project progresses. Generally, placement of filter cake in the dry stack facility would take place in the spring, summer and fall.
  - **Underground Storage**: The backfill system would deliver the remaining, approximately 40% of the tailings to the underground mine. Engineered tailings backfill would be created by mixing thickened tailings, tailings filter cake, and a binder to achieve the desired engineered tailings backfill consistency to be pumped underground and placed in mined out stopes. The engineered tailings backfill target consistency range would be 69% to 81% solids. A small amount of cemented-slag binder (approximately 1 – 2 wt.%) would be added to the tailings to increase structural integrity and minimize movement of water.

- **Waste Rock**: Only waste rock generated during the construction period would be brought to surface. During operations, all waste rock would remain underground and be used as a component of the engineered backfill.
  - **Construction**: Less than 2 million tons (1.8 million tonnes) of waste rock would be brought to surface during the construction phase, primarily associated with excavation of the decline. Approximately 60% of this waste rock would be used in construction (geochemical testing would be conducted to confirm suitability for use in construction). There would be no long-term storage of the remaining waste rock on the surface. Sulfide-bearing waste rock brought to surface during construction would be placed on the surface in an engineered facility (i.e., lined stockpile with contact water collection) for up to four years. This rock would be processed through the mill within the first two years of operation.
  - **Operations**: During operations, all waste rock would remain underground as backfill. Waste rock placed in the stopes would be encapsulated in cemented tailings, thereby minimizing exposure to oxygen and water.
- **Water Management**: The mine water management system would be designed to prevent the discharge of contact water to the environment. Contact water would be used in the process water circuit as follows:
  - Contact water from the tailings management site would be returned to the mine site.
  - Underground mine water would be collected and delivered to the mine site contact water ponds for use in processing.
  - As practical, surface water would be diverted around the mine site and the tailings management site (i.e. non-contact water).

TMM's strategy to mine material management focuses first on elimination of ARD/ML risk, with engineering controls as a secondary or complementary action. Key aspects of TMM's waste management plan include minimizing the mass, sulfur content and exposure of any sulfidic material mined and brought to surface to prevent generation of ARD. The components of the mine design aimed at preventing/mitigating ARD/ML are presented in Section 4.

# 3.0 ARD/ML UNDERSTANDING - GEOCHEMICAL CHARACTERIZATION

An understanding of environmental geochemistry is a critical component of modern mining. Awareness of the impacts that historical and active mining can have on the environment and the implementation of regulations meant to guard against these impacts have resulted in increased focus on pre-mining characterization. For modern mines, geochemical characterization starts during the planning stage and continues through active mining, to inform water and waste management practices, and culminates in mine closure (Seal and Nordstrom 2015).

Considerable information is available regarding the environmental behavior of magmatic sulfide deposits in general and the Duluth Complex specifically. The polymetallic deposits of the Duluth Complex have been studied extensively by TMM and others. Although the stratigraphic sequence of individual deposits may vary, lithologic units over the Duluth Complex show remarkable consistency in terms of their geochemical, and therefore environmental, characteristics.

The information available provides a fundamental understanding of the expected environmental behavior of the materials originating from the Project. Key findings regarding the environmental behavior of Duluth Complex rocks include:

- Sulfur content and sulfide mineralogy are the controlling factors for the rate and severity of ARD generation from Duluth Complex rocks.
- The silicate neutralization potential (NP) present in Duluth Complex rocks is available and sufficient to maintain circum-neutral pH conditions for extended periods (i.e. decades) for rock with low total sulfur content. For higher total sulfur content rock, silicate NP is responsible for a delay in the development of ARD, thereby allowing time for implementation of appropriate engineering controls.
- Relative sulfide mineral reactivity (pyrrhotite > pentlandite > pyrite > chalcopyrite) is consistent with literature rates reported by others (e.g., Jambor et al. 2005).

In this section, the research conducted by others on the geochemical behavior of Duluth Complex rock is presented (Section 3.1), followed by a summary of geochemical characterization work done by TMM spanning more than a decade (Section 3.2). The collective body of research applicable to the TMM Project (Section 3.3) as well as the geo-environmental model approach (Section 3.4) are used to inform the Project's ARD/ML conceptual model (Section 3.5).

Two limitations frequently cited in the industry's ability to accurately predict ARD potential for a future mine include: 1) the scale of testing programs (i.e. laboratory as opposed to field), and 2) the limited duration of so-called long-term testing programs (e.g., kinetic testing). Both of these limitations have been or are being addressed for the Project. As discussed in Section 3.1, the Duluth Complex is unique in that long-duration kinetic testing has been conducted. To address the scale of testing, the environmental behavior of the Project materials is being confirmed by the Project's MMCP discussed in Section 3.2.

Kinetic tests are routinely used as a tool in understanding the long-term weathering behavior of a material, including the lag time to the generation of ARD for a PAG material. Studies of the potential for ARD generation from Duluth Complex rocks have been conducted at the laboratory and field scale by United States government research organizations (i.e. Minnesota Department of Natural Resources [MDNR] and the United States Geological Survey [USGS]) and private industry. These studies have included kinetic testing programs that have operated for years, sometimes longer than a decade, and to the author's knowledge, represent the longest laboratory testing programs executed by anyone in the industry.

## 3.1 Duluth Complex Geochemical Characterization by Others

The environmental behavior of Duluth Complex rocks has been studied by MDNR, the USGS and PolyMet Mining Corporation (PolyMet 2015), a privately-held company proposing to develop another Cu-Ni-PGE project in the Duluth Complex. Research by these organizations and details of TMM's MMCP are summarized in this section.

### 3.1.1 MDNR Research

Since the late 1970s, MDNR has studied the potential for ARD generation from Duluth Complex rocks at both the laboratory and field scale. The extensive duration of their testing programs represents a data set that is unique in the mining industry.

MDNR has studied the weathering behavior of development rock (i.e. waste rock), tailings and low-grade ore. Details of selected MDNR studies are summarized in Table 2.

#### *3.1.1.1 Laboratory Kinetic Testing Methodologies*

Kinetic testing is conducted to assess the rate of sulfide mineral weathering and release of mass from a solid material sample. Laboratory tests are designed to accelerate the rate of weathering relative to field conditions. MDNR kinetic testing has included two methodologies:  the industry-standard humidity cell test (HCT; ASTM 1996, 2007) and the MDNR reactor.

The standard HCT test is performed in a cylindrical cell. Within the cell, a 1-kilogram sample of solid material crushed to minus ¼ inch (waste rock or ore) is leached with a fixed-volume aqueous leach. No particle size reduction is necessary for tailings. The test procedure consists of weekly cycles, wherein for three days the cell is provided a steady flow of dry air (less than 10% oxygen), and for three days the cell is supplied with a steady flow of water saturated air (95% relative humidity). The cell is leached with a fixed volume of water on Day 7. The composition of the leachate is then determined by chemical analysis.

A comparison of the HCT and MDNR reactor tests is shown in Table 3. The MDNR reactor test procedure also involves weekly leaching of a solid material. Between leaches, the sample is exposed to air under ambient conditions. In comparison to the HCT procedure, the sample mass is lower (i.e. 75 grams versus 1 kilogram) and the particle size reduction is much greater (i.e. the MDNR reactor sample is finer than the HCT sample). The MDNR reactor weekly solution to solid ratio is higher than the HCT test (Table 3).

#### *3.1.1.2 Results from the Development Rock and Low-Grade Ore Study*

The principal finding of decades of research is that the sulfur content of the Duluth complex rocks, in association with sulfide mineralogy, is the controlling factor for the rate and severity of ARD generation. At low total sulfur contents, silicate NP is sufficient to neutralize acidity and maintain neutral pH conditions.

Minimum leachate pH versus sulfur total content for the MDNR waste rock and low-grade ore samples from Studies 1 to 4 (Table 3) is shown in Figure 3. Results from the PolyMet testing program (discussed in Section 3.1.2) are included for comparison. Figure 3 includes data from numerous studies with variable test durations (months to years), test methodologies (HCT, MDNR reactor and stockpile) and scales (laboratory and field). Despite these differences, this figure shows a systematic relationship between minimum leachate pH and total sulfur content. This relationship can be used to define a threshold for ARD-generating material (approximately 0.2 wt.%). Below this threshold, the test results indicate that the neutralization potential, primarily from silicate minerals, is sufficient to neutralize acidity. This finding has important ramifications in terms of mine material management, for instance allowing the segregation of non-PAG (NPAG) versus PAG material based on the total sulfur content.

Additional observations from the MDNR studies are summarized as follows:

- **Test Duration:** The MDNR studies provide insight into the duration of kinetic testing required to inform material management decisions for Duluth Complex rock. Study 2 (Kellogg et al. 2014) in Table 2 provided an update to the test work presented in Study 1 (Lapakko and Antonson 1992). Studies 1 and 2 presented MDNR reactor results for 16 samples at the conclusion of 150 weeks and up to 24 years of testing, respectively. These studies grouped samples by sulfur content based on consistency in minimum leachate pH measured during testing. As shown in Table 4, the sulfur groupings for the two studies were similar with the only significant change being a reclassification of the 0.4 wt.% sulfur from Group 1 to Group 2. Although slight decreases in pH were observed following a longer period of testing, the pH minimums reached over the longer period of testing in Study 2 are unlikely to result in a change in the approach to material management. Toward the conclusion of Study 2 testing, an increasing pH trend was observed for most Group 2 and 3 samples. Based on drainage pH alone, Study 2 concluded that Group 1 development rock would probably require no rigorous reclamation, acknowledging that sulfate and metal leaching may still need to be addressed. The same conclusion could have been reached at the termination of Study 1.
- **Relative Sulfide Reactivity:** Study 2 (Kellogg et al. 2014) noted significant depletion in sulfide minerals over the period of testing. A 50% decrease in pyrrhotite was measured without any significant decrease in chalcopyrite. Study results were consistent with the relative rates of sulfide oxidation reported by Jambor (2005) (i.e. pyrrhotite > pentlandite > pyrite > chalcopyrite).
- **Particle Size Effect on Sulfide Reactivity:** Study 3 (Lapakko et al. 2013a) noted an increase in the rate of sulfide oxidation as particle size decreased and surface area increased. This observation is consistent with general geochemical principles.

#### *3.1.1.3 Results from the Tailings Study*

MDNR conducted a 10-year laboratory study on weathering of Duluth Complex tailings (Lapakko et al. 2013b). The geochemical characteristics of the tailings sample are shown in Table 5. The total sulfur content of the tailings was 0.2 wt.% and the primary sulfide mineral was pyrrhotite. The NP data indicated that carbonates represented only a small fraction of the total NP, as expected for Duluth Complex rocks.

The testing program included six MDNR reactors and two humidity cells, operated in accordance with ASTM D5744-96 (ASTM 1996). Circum-neutral pH conditions were maintained in all tests over the 10-year period. HCT pH values generally declined over the period of testing from near 8 to 6.8. Neutralization was attributed to dissolution of trace calcite (early stages of testing) and silicate mineral dissolution, specifically labradorite (=plagioclase), augite (=pyroxene), olivine and biotite. The results from this investigation were consistent with those from the MDNR development rock and low-grade ore studies in terms of the relationship between ARD potential and total sulfur content.

### 3.1.2 PolyMet Research

PolyMet proposes to develop the NorthMet Deposit, a Cu-Ni-Co-Pt-Pd-Ag deposit within the Duluth Complex. The deposit occurs over a length of approximately 2.5 kilometers and is covered by a thin layer of glacial till (PolyMet 2015). PolyMet plans to develop the deposit by open pit mining. Disseminated copper-nickel-iron sulfides (i.e.

chalcopyrite, cubanite, pentlandite, and pyrrhotite) and associated PGE mineralization will be extracted from several igneous stratigraphic horizons (SRK 2007a).

PolyMet has performed a comprehensive mine materials characterization program. At the time of submittal of their draft Environmental Impact Statement (EIS), kinetic testing results from 85 HCTs operated for 168 weeks were available (SRK 2009). Final leachate pH versus total sulfur content for the 85 humidity cells is shown in Figure 4 (this figure includes three ore samples). The test results are summarized as follows:

- During the period of kinetic testing, acidic conditions (defined as pH < 4.5) were established in eight cells. The total sulfur contents of these eight samples ranged from 0.86 to 5.7 wt.%.
- All samples with total sulfur contents less than 0.1 wt.% reported circum-neutral final leachate pH values (between approximately 6.5 and 7.5).
- Acidic conditions were not reached before 60 weeks of testing in any of the samples with a total sulfur content less than 3.0 wt.%. The observed lag time to ARD was attributed to buffering by silicate minerals (i.e. plagioclase and olivine).

Results of the geochemical testing program were used to classify waste rock in the final EIS (MDNR et al. 2015). Four waste rock classes were defined on the basis of total sulfur concentration (Table 6). Greater than 90% of the waste rock that will be generated by the PolyMet mine is designated as having low to medium potential to generate ARD. PolyMet also predicts that the lag time to the onset of ARD for Class 2 and 3 waste rock will be greater than five years (PolyMet 2015) (Figure 5).

Other key findings from the PolyMet program include (SRK 2007a):

- **Rate of Sulfide Oxidation** – The rate of sulfide oxidation is proportional to the total sulfur content, while the sulfide mineralogy plays a role as well. Other variables (e.g., rock type, position in intrusive stratigraphy) do not appear to be important.
- **Metal Leaching** – Solution pH is the primary control on metal leaching. In particular, nickel leaching increases as pH levels decline below 7.0.

The results from this investigation were consistent with those from the MDNR programs in terms of the relationship between ARD potential and total sulfur content.

### 3.1.3 USGS Study

#### *3.1.3.1 Determination of Neutralization Potential*

The ARD potential is determined by the balance between the acid generation potential of a material (i.e. sulfide concentration) and the neutralization potential (NP). NP is a measurement of the amount of alkaline or basic material in a rock or soil. There are many minerals capable of acid neutralization; however, their reaction mechanisms and rates vary widely. Effective NP is defined as “the acid neutralization that can neutralize internal and external acidity inputs sufficiently to maintain near-neutral pH drainage” (MEND 2009). For many mine materials, effective NP includes only the contribution from carbonate minerals calcite and dolomite. For the Duluth Complex rocks, NP is associated with the dissolution of silicate minerals.

The static analytical testing methods used to estimate the NP of a material broadly fall in two categories:

- **Bulk NP** – Standard analytical methods for the determination of bulk NP measure a contribution from both carbonate and non-carbonate minerals with buffering capacity. The NP of a material is typically estimated by acid digestion followed by back-titration to determine the quantity of acid consumed by the sample.
- **Carbonate NP** – Standard methods to determine the NP of a material based on its carbonate content involve either direct (i.e. mineralogical analysis) or indirect (i.e. measurement of total inorganic carbon (TIC) or total carbon (TC) assumed to be present as calcite) measurement of the carbonate content of a sample.

For Duluth Complex rocks, carbonate NP is low or non-existent and therefore determination of carbonate NP is not informative. However, mineralogical analysis, which can be used to estimate carbonate NP, can also be used to estimate silicate mineral NP. Bulk NP analyses conducted on monomineralic and near-monomineralic samples provide data on mineral contributions to NP (e.g., Jambor et al. 2000, 2002, 2003, and 2006). This information, in association with mineralogical analysis results, can be used to estimate non-carbonate mineral NP.

#### 3.1.3.2 Results

Schulte et al. (2016) evaluated the NP associated with the silicate minerals present in Duluth Complex rock. Two of the silicate minerals that have the highest NP values are present in these rocks (i.e. olivine and calcic plagioclase). Schulte calculated the NP contribution from silicate minerals for Duluth Complex drill core samples based on the NP values for the individual minerals presented in Table 7. The study included nine samples from the Maturi Deposit.

Results of this study are shown in Figure 6 (reproduced from Schulte et al. [2016]). Samples from the Maturi Deposit are identified by the designation DU-14. For most Maturi samples, NP was greater than AP (Figure 6-A). Assuming virtually all (e.g., 90%) of the sulfide in ore samples reports to the concentrate during processing, NP is greater than AP for all samples (Figure 6-B). The authors concluded that the NP in these cores may be sufficient to neutralize the acid generated by sulfides.

## 3.2 Twin Metals Minnesota Mine Materials Characterization Program

Although the research performed by others (Section 3.1) provides a fundamental understanding of the expected environmental behavior of the materials originating from the Project, the behavior of the Project materials is being confirmed by the Project's MMCP described in this section. This characterization program is a comprehensive and thorough effort that stands on its own merits.

TMM's commitment to comprehensive characterization of the geochemical behavior of the Maturi Deposit began during exploration drilling. In cooperation with MDNR, they have developed and implemented a broad laboratory-based material characterization program. This testing program is ongoing.

Key findings of the studies to date include:

- Copper sulfides are the dominant sulfide minerals in the Maturi Deposit. From an environmental perspective, this is beneficial as these sulfides have lower reactivity and acid generation potential compared to iron sulfides (i.e. pyrite and pyrrhotite).
- Most of the waste rock and ore samples tested to date are classified as non-acid generating (NPAG) based on the results of static and kinetic testing.
- Test work to date indicates no ARD potential for the tailings due to their low sulfur content. This conclusion is consistent with studies by MDNR and USGS (Lapakko et al. 2013b; Schulte et al. 2016).

### 3.2.1 Sulfide Type and Occurrence

Geochemical characterization of Duluth Complex rocks has indicated that total sulfur content and sulfide mineralogy are the most important factors in the assessment of environmental behavior. The sulfide minerals identified in the Maturi Deposit include (in general order of importance) (TMM 2021a):

- chalcopyrite [$CuFeS_2$]
- cubanite [$CuFe_2S_3$]
- pentlandite [$(Ni,Fe)_9S_8$]
- pyrrhotite [$Fe_{1-x}S$]
- bornite [$Cu_5FeS_4$], pyrite [FeS], covellite [CuS] and millerite [NiS] (present in trace amounts)

Sulfide distribution throughout the deposit is as follows (TMM 2021a):

- **BMZ (Ore)**: The mineralized zone immediately above the footwall contact with the SKI (i.e. lower BMZ) consists of 1 to 5% disseminated chalcopyrite, cubanite, pentlandite and pyrrhotite. The characteristic sulfide mineral distribution of subunits S2 and S3 is shown in Figure 7. Copper sulfides are the dominant sulfide minerals. Subunit S2 contains a higher proportion of pyrrhotite than S3.
- **Hanging Wall**: Magmatic sulfide mineralization in the SKI is restricted to the BMZ and rarely occurs in the hanging wall.

  Total sulfur results for four Maturi holes that underwent comprehensive assay over their entire depth are shown in Figure 8. The number of samples for each hole ranges from 360 to 441. In each total sulfur profile, the extent of the ore zone (based on a copper cut-off of 0.3 wt.%) is identified in yellow.

  These figures show that elevated sulfur concentrations (>0.5 wt.%) generally occur within the immediate vicinity of the ore zone. The average and median sulfur concentrations for samples located outside the ore zone are 0.07 wt.% and 0.04 wt.%, respectively (1,490 determinations).
- **Footwall**: Magmatic sulfide mineralization is commonly present in the upper 30 feet of the footwall GRB. The sulfide mineral assemblage in the footwall is dominated by chalcopyrite, cubanite, pentlandite and pyrrhotite with rare bornite.

The sulfide minerals in the Maturi deposit and their relative potential for acid generation are listed in Table 8. From an environmental perspective, pyrrhotite is the sulfide of most interest. This is because it is one of the most reactive sulfide minerals and generates acid upon oxidation. The other sulfide minerals identified will oxidize as well, but do so at a slower rate and may not generate acid, unless ferric iron is the oxidant. When acidic conditions are reached, and ferric iron becomes the oxidant, acid is generated through the oxidation of chalcopyrite, cubanite and pentlandite (Plumlee 1999). These conditions (i.e. pH <3.5) are only reached for material with total sulfur greater than approximately 1% (Figure 3), which is a small proportion of overall Project material and virtually all ore (Figure 8).

### 3.2.2 Overview of Mine Materials Characterization Program

In consultation with MDNR, TMM developed a robust geochemical characterization program, the MMCP. This program comprehensively evaluates the environmental geochemistry of the Project, and addresses the following matters:

- Acid-rock drainage (ARD)
- Metal leaching (ML) under acidic, neutral or alkaline conditions
- Potential for discharges of sulfate and other non-metallic constituents
- Potential for labile mercury
- Potential for labile (asbestiform) fibers

The components of the analytical testing program are shown in Table 9. This industry-standard analytical program is consistent with the requirements specified in Minnesota Rule 6132.1000 Subparts 1 and 2 (Office of Revisor of Statutes - State of Minnesota 2008).

Implementation of the testing program follows a phased approach and includes both static (short-term) and kinetic (long-term) testing. The objective of static testing is to describe the bulk chemical characteristics of a material. These tests are designed to evaluate the potential of a particular rock type to leach metals or generate acid. Static testing is typically the first phase of geochemical characterization, and routinely is a precursor to kinetic testing. Although the results of static testing may initially indicate a potential for ARD/ML, kinetic testing is required to verify whether the various ARD/ML potentials identified will indeed be realized.

TMM's MMCP is ongoing. To date, the testing program has included geochemical characterization of more than 200 samples. Sample distribution by material (waste rock, ore and tailings) and test type (static or kinetic) is shown in Table 10.

MDNR has been engaged though all stages of design and implementation of the program. As testing results become available, results and interpretation are communicated to MDNR who have provided ongoing feedback. Ongoing engagement throughout the entire process is a key component in ensuring a robust and defensible data set that is sufficient to inform decisions on appropriate material management strategies during operations and closure.

The specific tests conducted as part of the MMCP are summarized as follows:

- **Chemical Composition**: Characterization of a material's chemical composition is fundamental to understanding its environmental behavior. The results from solid-phase chemical analysis can be used to infer which elements are of potential environmental concern, although a high concentration of a particular element does not necessarily imply that this element will indeed be mobilized in concentrations that may lead to environmental impacts. Characterization of the trace metal composition of a sample is typically a two-step process that includes an acid digestion to release elements into the solution phase followed by analysis of the elements in the resulting digestate. Methods of trace metals analysis for the Project include:
  - Four acid digestion followed by inductively coupled plasma mass spectrometry (ICP-MS) and ICP optical emission spectrometry (ICP-OES) analyses (most elements)
  - Three acid digestion followed by ICP-MS analysis (As, Sb and Se)

- Aqua regia digestion followed by cold-vapor atomic adsorption analysis (Hg)

  The major rock forming elements have been determined by x-ray fluorescence (XRF). This testing was conducted on all material types.

- **ARD Potential**: A determination of the ARD potential is conducted to predict the acid generation characteristics of a material and is typically based on the relative difference between the material's net acid generation potential and net acid neutralization potential. ARD potential is commonly determined using ABA, which involves measurement of sulfur species and neutralization potential (NP). An accurate and meaningful measurement of NP is typically premised on the fact that the majority of the NP is provided by carbonate minerals. In the case of the Project, carbonates are largely absent, while any NP is instead contributed by silicate minerals such as olivines and plagioclase. Therefore, estimates for acid potential (AP) and NP from ABA are refined as needed using mineralogical information.

  ABA analysis has included determination of the following:

  - Sulfur species (total, sulfate, sulfide)
  - Bulk NP (modified Sobek)
  - Total inorganic carbon (TIC)
  - Paste pH

  In addition to standard ABA analysis, the testing program includes net acid generation (NAG) testing. In combination with ABA results, the NAG test provides a powerful tool for prediction of ARD generation. The NAG procedure uses a strong oxidant (hydrogen peroxide) to rapidly oxidize sulfide minerals in a crushed rock sample (AMIRA 2002). The NP of the sample then can be directly challenged by the acidity generated by rapidly oxidizing sulfides. If the sample has sufficient available NP, the alkalinity of the whole rock will not be entirely depleted, and the system is expected to have the capacity to remain circum-neutral. If there is inadequate available NP, then the pH of the test solution will fall below 4.5 and there will be net acidity rather than net alkalinity. In this case, a sample shows potential for acid generation.

  The ABA and NAG tests are both designed to evaluate ARD potential. The use of two methods allows an independent evaluation of ARD potential is intended to result in a more robust characterization program. This testing was conducted on all material types.

- **Mineralogical and Petrological Analysis**: Information on the mineralogical composition, mineral assemblages, and textural relationships was obtained as follows:

  - **Mineralogical Analysis**: Identification and quantification of both the crystalline and amorphous phases present in a rock sample.
  - **Petrological Analysis**: Petrology is the study of the composition, origin, structure and formation of rocks. Petrography, a branch of petrology, focuses on the description and classification of rocks through the use of microscopic examination. The objective of petrological analysis by microscopic examination is to characterize mineral modal abundance, mineral grain size, mineral texture, and mineral alteration. Petrological analysis focused on identification and characterization of sulfide minerals and neutralization minerals (i.e. carbonates and silicates).

The mineralogical information is used in the interpretation of both static and kinetic testing data and is an essential component of mine water quality prediction because mineralogical properties determine the physical and geochemical stability and reaction rates of geologic materials and mine wastes (INAP 2014). The mineralogical and petrological evaluation included visual logging, x-ray diffraction (XRD), quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN), optical microscopy, and electron probe micro-analyzer analysis. This testing was conducted on all material types.

- **Short-Term Leach Testing**: This testing was conducted to identify the readily-soluble fraction of select samples. The method used was the Synthetic Precipitation Leaching Procedure (Method 1312, USEPA 1994), which aims to simulate the interaction between a solid material and meteoric water (i.e. rainfall). The method does not account for transient geochemical reactions such as sulfide oxidation, but only simulates conditions representative of short-term contact. The leachates were analyzed for a comprehensive suite of parameters. This testing was conducted on the backfill binder materials only.
- **Kinetic Testing**: The kinetic testing methods included in the geochemical characterization program are the following:
  - **Humidity Cell Testing**: HCTs are long-term tests typically conducted over a period of weeks to years. They consist of repetitive leaching cycles aimed at accelerating the chemical processes of interest, i.e. sulfide oxidation and corresponding reaction of neutralizing minerals. The method used was the ASTM D5744-18 method (ASTM 2018), which represents weathering under exposed (i.e. atmospheric) conditions. The HCT leachates were analyzed for a comprehensive suite of parameters to determine contact water quality and reaction rates for use in source term development for waste rock, ore and tailings. This testing was conducted on all material types.
  - **Diffusion Testing**: Diffusion tests are tests aimed at determining mass transfer rates (release rates) of inorganic analytes present in a monolithic or compacted granular material, under inundated, diffusion-controlled release conditions, as a function of leaching time. Due to the low permeability of cemented tailings, a diffusion release test generates the most representative data for evaluating releases from cemented paste under flooded conditions (Schafer 2016). The method used was the USEPA Method 1315 (USEPA 2017). The leachate analytical suite was comprehensive, and consistent with that of the HCT program. Results were used to determine contact water quality and develop source terms for cemented tailings. This testing was performed on cemented tailings only.
  - **Flooded Column Leaching**: Flooded column leaching is planned to determine the long-term leachability of materials that are inundated as the underground mine floods after cessation of mining. Testing will consist of repetitive leaching cycles under fully saturated condition. The resulting leachates will be analyzed for a comprehensive suite of parameters to determine contact water quality and reaction rates for use in post-closure source term development.

### 3.2.3 Results of Mine Materials Characterization Program

A number of criteria exist to characterize a sample as potentially acid generating (PAG) and non-potentially acid generating (NPAG) using ABA and/or NAG results. The most common approaches are those based on the use of the net potential ratio (NPR = NP/AP) and the net neutralization potential

(NNP = NP – AP). No single NPR ratio or NNP value has been identified as having universal applicability in terms of predicting acid generation. The actual threshold values for a particular solid are material-specific, and depend on many factors, including the amounts and types of acid generating and neutralizing minerals, their morphology, their grain size, their crystallinity, their chemical composition, their paragenesis, the material's texture, and the site-specific exposure conditions.

Guidelines for evaluating acid generation potential of mine materials presented by MEND (2009) are summarized in Table 11. These guidelines, in association with NAG pH values are applied in evaluating Project ABA results. A NAG pH of 4.5 is generally accepted as the threshold between PAG and NPAG material (AMIRA 2002).

Based on the results of the static testing to date (i.e. neutralization potential ratio [NPR] and NAG pH), less than 15% of waste rock and ore samples are classified as having an ARD potential (defined as an NPR value less than 2 and a NAG pH value of less than 4.5). NPR values have been calculated using bulk NP and AP calculated from total sulfur (i.e. assuming all sulfur is present as pyrite, which is a conservative approach) (Figures 9 and 10). Almost all PAG samples represent BMZ and mineralized GRB located near the contact with the BMZ. NAG pH values less than 4.5 and NPR values less than 2 are observed for total sulfur contents of approximately 0.5 wt.% and greater. Only a few waste rock samples with total sulfur concentrations between 0.2 and 0.5 wt.%, mostly from the GRB, reported NPR values less than 2.

In general, the predictions of long-term ARD potential resulting from the kinetic testing of waste rock and ore are in good agreement with those based on the results from the ABA and NAG testing. The evaluation of the combined static and kinetic testing results from the MMCP indicates that hanging wall material and ore with a total sulfur content greater than approximately 0.5 wt.% (hanging wall) and 0.4 wt.% (ore) are PAG. For the GRB footwall, this threshold is in the 0.2 to 0.3 wt.% range. These findings for the ultramafic rocks of the hanging wall and ore are consistent with those from earlier studies of Duluth Complex materials. Metal and sulfate leaching for these samples is generally low to very low. No samples with total sulfur <0.1 wt.% are identified as PAG based on the static and kinetic testing results, indicating that the preliminary cutoff established for construction rock is protective of the environment.

The results from static and kinetic testing of tailings indicate a low to non-existent potential for ARD. The fact that the tailings are NPAG is consistent with findings from studies that included testing of Duluth Complex rock over periods of up to 18 years (e.g., SRK 2007a; Kellogg et al. 2014). In these studies, it was identified that mafic/ultramafic material containing less than 0.4 wt.% total sulfur does not generate acidic leachates over the long term. The NPAG character of the tailings is also consistent with the findings from the tailings characterization program conducted by PolyMet (SRK 2007b) and Lapakko et al. (2013b), in which it was demonstrated that tailings containing less than 0.12 and 0.2 wt.% total sulfur, respectively, were non acid generating.

## 3.3 Use of Existing Studies

TMM makes use of the research conducted by others to supplement the extensive Project-specific characterization program. Use of the research by others to characterize the potential for ARD/ML considers the following with regards to the applicability of earlier studies to the Project:

- **Sulfide Occurrence**: Pyrrhotite was the dominant sulfide in the MDNR studies (Lapakko and Antonson 1992; Kellogg et al. 2014); chalcopyrite typically is the dominant sulfide in the Maturi Deposit. Pyrrhotite is much more reactive than chalcopyrite. For a given total sulfur concentration, the lag time to ARD for the Project materials is, therefore, expected to be longer than the lag time to ARD for the MDNR samples.
- **Lag Time to ARD:** There is widespread acceptance in the industry that laboratory studies accelerate the rate of weathering compared to field conditions; however, due to the many factors that influence laboratory

versus field behavior, there is no universal approach to the application of laboratory results to predict field behavior. The original ASTM HCT method stated that “*this laboratory test method has accelerated metal-mine waste-rock weathering rates by at least an order of magnitude greater than observed field rates*” (ASTM 1996). This statement has been removed from the most recent revision of the testing procedure. ASTM (2018) instead cites examples of accelerated weathering in the laboratory compared to the field, including an example for Duluth Complex rock, as follows: *“rates observed in laboratory tests of metal-mine rock have been reported to be 3 to 8 times those for small-scale field test piles of Duluth Complex rock”* (Lapakko 1994).

Accelerated weathering in the laboratory versus the field is in part due to particle size reduction (i.e. consistent with the geochemical principle that mineral reactivity increases with a decrease in particle size due to an increase in surface area). MDNR observed higher rates of sulfide oxidation using the MDNR reactor methodology compared to standard HCT testing (Lapakko et al. 2013a). It is notable that just as sulfide reactivity increases as particle size decreases, so does available NP reactivity. Application of laboratory testing data to the Project takes into account the effects of particle size.

## 3.4 Geo-Environmental Model

Geo-environmental models are a compilation of geologic, geochemical, geophysical, hydrologic, and engineering information pertaining to the environmental behavior of geologically similar mineral deposits pre- and post-mining and mineral processing. Such models are often used to provide a priori information about expected water qualities originating from a particular deposit type, including compositional variability associated with its mining effluents, wastes, and mineral processing facilities (Plumlee et al. 1999).

Mine drainage from magmatic sulfide deposits can range from acidic to alkaline depending on the degree of interaction between acid waters, generated by sulfide oxidation, and the reactive mafic and ultramafic minerals such as olivine, pyroxenes, and plagioclase. Metals enriched in these mine waters typically include copper, nickel and zinc (Plumlee et al. 1999).

Based on the work conducted by MDNR and PolyMet, the ARD/ML potential of lithologic units present in the Project (with the exception of the GRB), is very well understood. In terms of ARD potential, a strong correlation has been identified between total sulfur content and rate of sulfide oxidation. In terms of metal leaching, an increase in nickel and cobalt leachate concentrations was observed for the PolyMet samples as leachate pH values declined below 7. When pH values dropped below 5, coincident increases in sulfate, nickel, cobalt and copper concentrations occurred. These relationships are consistent with geochemical principles and observations from other magmatic sulfide deposits around the globe (Plumlee et al. 1999).

Ficklin diagrams are a tool used in geo-environmental assessments. The traditional Ficklin plot is a scattergram in which the sum of the base metals zinc (Zn), copper (Cu), lead (Pb), cadmium (Cd), cobalt (Co), and nickel (Ni) is plotted against pH. Figure 11 (reproduced from Plumlee et al. 1999) is a Ficklin plot presenting observed water qualities for magmatic sulfide deposits. This figure presents data from the Duluth Complex and the Stillwater Complex in Montana. The range in mine water qualities from circum-neutral with low metal concentrations to acidic with elevated metal concentrations is attributed to a range in total sulfur concentrations. The Stillwater Mine is the only operating PGE mine in the Unites States. This site was included in a study comparing actual and predicted mine water qualities (Kuipers et al. 2006). The mine has been in operation since 1986. As stated in Kuipers et al. (2006), in 2003, a comprehensive water quality review of pre- and post-mining water quality concluded that “over the approximately 18 years of mine life no noticeable impacts (compliance with Montana non-degradation water quality standards) to water quality in the Stillwater River have occurred due to the operation of the Stillwater Mine. There were no discernible impacts with the exception of increased nitrogen concentrations, which are from mining operations."

Ficklin diagrams using water quality data from the TMM Project are presented in Figures 12 and 13. Leachate results from kinetic testing of the waste rock, ore and tailings show low metals concentrations in association with circum-neutral pH conditions. To date, acidic pH conditions have only been realized for a few of the ore and waste rock samples with the highest sulfide concentrations.

## 3.5 Twin Metals Minnesota ARD/ML Conceptual Model

Extensive research by others has indicated that sulfur content and sulfide mineralogy are the controlling factors for the rate and severity of ARD generation from Duluth Complex rocks. The project-specific testing conducted by TMM as part of the MMCP has confirmed, and is expected to continue to confirm, this observation. The silicate mineral NP present in Duluth Complex rocks is available and sufficient to maintain circum-neutral pH conditions for extended periods (i.e. decades and beyond, based on the results of the MMCP) for rock with low total sulfur content. For material with higher total sulfur contents, silicate NP is responsible for a delay in the development of ARD, thereby allowing time for implementation of appropriate engineering controls. The lag time to ARD is also related to sulfur content (i.e. lag time decreases as sulfur content increases).

Studies by MDNR and PolyMet provide an initial indication on the expected lag time to ARD for high sulfur content rock. However, it is likely that these studies overpredict the rate of sulfide oxidation (i.e. under predict lag time to ARD) relative to Project materials due to 1) differences in sulfide mineralogy between these studies and the Project (i.e. relative concentrations of copper sulfides and iron sulfides), and 2) the methodology used in kinetic testing (i.e. enhanced particle size reduction and increased mineral reactivity due to the use of the MDNR reactor). Project-specific kinetic testing is being performed to determine Project-specific lag times to ARD development. HCT testing to date for both waste rock and ore has demonstrated a lag time of greater than one year, under laboratory conditions, to the onset of acid generation for samples classified as PAG based on the static testing results.

The current conceptual model for the ARD/ML potential of Project materials prior to implementation of engineering controls is as follows:

- **Tailings**: Non-acid generating due to low sulfur content (≤ 0.2 wt.%).
- **Hanging Wall Waste Rock and Wall Rock**: No to low ARD potential due to low sulfur content and the presence of silicate minerals with available neutralization potential.
- **Footwall Waste Rock and Wall Rock**: Uncertain ARD potential due to variability in total sulfur concentration (i.e. mineralization present in some parts of the footwall) and uncertainty in the available NP of the GRB. Where sulfides are present, lag time to ARD will be related to total sulfur content. Where mineralization (i.e. sulfide minerals) is absent, the ARD potential of the GRB is characterized as low. The presence of sulfide mineralization in the GRB is associated with the BMZ.
- **Ore**: Likely ARD potential due to the presence of sulfides at percent levels. Project-specific testing is being conducted to determine the lag time to ARD.

All materials have the potential for low-level metal and sulfate leaching under circum-neutral pH conditions. If acidic conditions were to develop, metal and sulfate concentrations would increase. Site-specific water quality modelling is being conducted to identify the need for management of contact water.

### 3.5.1 Comparison to Other Deposits

In this paper, the importance of sulfur content in ARD generation has been mentioned repeatedly. In general, the ARD risk associated with an ore deposit is proportional to the amount of sulfides present and inversely proportional to the amount of NP available. However, for the same deposit type, sulfide concentrations, and thus ARD potential, can be highly variable. For this reason, Seal (2014) cautions against the blanket use of the term “sulfide mining”. Site-specific assessments, which consider the characteristics of both the source material (i.e. a mine waste containing sulfide) and the receiving environment, are required to evaluate the potential impacts from each individual mining project and the mine waste and water management measures required to prevent and mitigate these impacts.

Seal et al. (2014) contrast Cu-Ni-PGM ores in the Lake Superior Region by comparing the Eagle Mine in Michigan to the ore bodies of the Duluth Complex. Although both sets of deposits are considered sulfidic deposits and, therefore, represent “sulfide mining”, the sulfur content of the Duluth Complex ore bodies is up to a few percent total sulfur while the sulfur content of the Eagle deposit is tens of percent (i.e. 13 to 36 wt.%). Another fundamental difference in the ARD potential of these projects relates to the fate of the sulfur during mineral processing. For the Project, virtually all sulfur will report to the concentrates, whereas most of the sulfur at the Eagle Mine is retained in the tailings. For these two reasons, the sulfur content, and therefore ARD potential, of the Eagle Mine waste rock and tailings is significantly greater than that of the proposed Project.

Consistent with the Project’s conceptual model, Seal notes that even when ARD potential is low, the potential for risks to human health and the environment from trace metals mobility at neutral pH must be considered (e.g., Ni and Cu).

# 4.0 ARD/ML PREVENTION AND MITIGATION – MINE DESIGN AND MATERIAL MANAGEMENT

Prior to mining, the ARD/ML potential of Project materials would be well understood. When an ARD and/or ML risk is identified, state-of-the-art engineering controls would be implemented to mitigate any potential environmental impacts.

TMM's strategy to mine material management focuses first on **elimination** of ARD/ML risk, with **engineering controls** as a secondary or complementary action.

Key aspects of mine design and material management include:

- **Underground Mine**: Resource development would be by underground mining as opposed to open pit.
  - The environmental benefits of underground mining, as compared to an open pit, include reduced land disturbance and waste generation and the avoidance of a pit lake or other large surface feature at closure.
  - The total rock (ore and waste rock) disturbance during life of mine is approximately 207 million tons (188 million tonnes), of which the majority (~85%) is associated with the ore.
  - TMM would minimize the duration of open stopes to limit sulfide exposure.
  - All waste rock generated during operations and approximately 40% of the tailings (with a 1 to 2% cement slag binder) would be used as mine backfill. Flooding of the underground following closure would result in inundation of these materials, a proven method to halt sulfide oxidation.
  - Collection and use of underground mine water in the process water circuit during operations.
- **Dry Stack Tailings Facility:** Approximately 60% of the tailings would be stored in a dry stack facility.
  - Storage in a dry stack facility, as opposed to a traditional slurry impoundment, is current industry best practice.
  - Tailings dewatering would limit the amount of entrained pore water within the facility and maximize return of water to processing.
  - By design, because virtually all of the sulfide minerals would be removed in the concentration process, the sulfur content of the tailings would be low (≤0.2%), which is below the threshold identified for acid generation.
  - The dry stack facility would be lined to prevent a seepage pathway to groundwater.
  - The dry stack tailings would be covered, and progressively reclaimed with native soil and vegetation as the project progresses.
- **Waste Rock**: Minimal waste rock will be generated by the mine. Only waste rock produced during the construction phase will be brought to surface. All waste rock generated during operations will remain underground.
  - Minimal storage of waste rock on surface both in terms of tonnage and duration.

- Use of a lined facility with contact water controls for any short-term storage (<4 years) of waste rock on surface.

## 4.1 Mine Design

The benefits of key aspects of TMM's mine design are discussed in this section.

### 4.1.1 Benefits of Underground vs. Open Pit Mining

Development of the resource by underground mining, as opposed to open pit mining, is a key component of the Project's mine material management. Environmental benefits of underground mining, as compared to an open pit, include reduced land disturbance and waste generation (tailings and development rock) (Environment Canada 2009).

Comparison of the TMM Project to the proposed PolyMet project (MDNR et al. 2015) allows for a direct assessment of the disturbance from an underground versus an open pit operation. The PolyMet project over a 20-year mine life will generate more than 200 million tons (180 million tonnes) of waste rock. Table 12 presents a comparison of waste rock management practices for the PolyMet and TMM projects:

- PolyMet:
  - 168 million tons (152 million tonnes) of Class 1 waste rock would be stored permanently on surface in an unlined facility.
  - 50 million tons (46 million tonnes) of Class 2, 3 and 4 waste rock would be stored temporarily on surface (up to 20 years) in a lined facility prior to relocation in an open pit.
- TMM would store the 1.2 million tons (1.1 million tonnes) of waste rock and ore generated during the construction phase in a temporary lined stockpile. The maximum period of storage on surface would be 3.5 years.

Polymet plans to relocate all Class 2, 3 and 4 waste rock to the East Pit. After rebound of the groundwater table and flooding of the pit, the resulting subaqueous disposal of waste rock in the pit would essentially halt any sulfide oxidation reactions. It should be noted that post-closure flooding of the underground TMM mine, containing essentially all waste rock in the form of backfill, would also essentially eliminate sulfide oxidation. As such, the ultimate ARD controls for the two projects for all or a portion of the waste rock are identical.

The Buckhorn Gold Mine in Republic, Washington provides another comparison of the relative disturbance and waste rock management from an underground versus open pit operation. The Buckhorn Mine, which entered closure in 2017, operated from 2008 to 2017. The underground mine was permitted in 2008 following an unsuccessful effort to permit an open pit mine in the late 1990s. At that time, the project's water rights were denied by the state Pollution Control Hearings Board because of concerns regarding the availability of water and impacts of the mine on local water resources (Banton 2008). The original EIS for the project evaluated development of the resource by both open pit and underground mining methods (USDA Forest Service and Washington State Department of Ecology 1995). The area of disturbance for the underground mine was estimated at 440 acres compared to between 766 and 927 for the open pit alternatives (4 open pit alternatives were evaluated). Similar to the TMM Project, the Buckhorn Mine has no surface storage of development rock (waste rock) at the end of operation. All development rock has been placed underground as backfill, with cement added depending on the ARD potential of the rock. The mine site has been reclaimed such that there are minimal visible effects of the mining operation. This is much different from an open pit mine that leaves a large mine void and rock stockpiles at the conclusion of mining.

### 4.1.2 Benefits of Thickened Tailings and Waste Rock Backfill

Research on the management of tailings through underground placement was summarized in a 2006 MEND report (Mehling Environmental Management Inc. 2006). This study acknowledged that data on groundwater quality impacts from backfill are limited; however, despite this data gap, use of backfill has generally been considered beneficial in reducing overall environmental impacts. Benefits of this technology include:

- Reduction in tailings and waste rock requiring surface disposal (i.e. decreased footprint)
- Reduction in potential for sulfide oxidation and metal leaching from thickened tailings due to:
  - Reduction in leachate generation due to reduction in free water
  - Lower permeability relative to waste rock, or in the case of the Project the damaged rock zone surrounding the mine stopes (i.e. preferential flow of groundwater around instead of through the tailings)
- Addition of cement increases NP and reduces permeability of the backfill
- Flooding at closure reduces potential for sulfide oxidation in tailings, waste rock and the damaged rock zone

Schafer (2016) notes that adding binders to thickened tailings increases strength, reduces the permeability of the tailings mass and the contact between water/tailings (i.e. monolithic behavior), thereby reducing the chemical mobility constituents such as metals. TMM would add 1 – 2% binder, comprising of a mixture of slag cement and ordinary Portland cement, to the tailings prior to underground placement, with the cemented tailings backfill accounting for approximately 40% of the total tailings mass generated over the life of mine.

### 4.1.3 Benefits of Dry Stacking of Filter Cake

Approximately 60% of the tailings would be dewatered to a filter cake consistency and compacted in a dry stack facility which would be lined, covered, and progressively reclaimed with native soil and vegetation as the project progresses. Associated water management features would include perimeter ditches and ponds to control contact water as well as a groundwater cutoff wall should any leakage through the underliner occur.

Use of a dry stack reduces ground disturbance relative to traditional slurry impoundments, eliminates the need for water-retaining structures such as dams, and significantly diminishes draindown from the tailings mass relative to a tailings slurry. Additionally, a lined dry stack facility would be highly geotechnically stable. Although ingress of oxygen is facilitated by the absence of significant moisture in the dry stack, due to the non acid generating nature of the tailings, formation of ARD is not of concern.

## 4.2 Summary – Mine Design and Mine Material Management

As outlined in the GARD Guide, the principal approach to the prevention and mitigation of ARD/ML is to apply methods that minimize the supply of the primary reactants for sulfide oxidation and/or maximize the amount and availability of acid neutralizing reactants. The GARD Guide presents methods for prevention of ARD/ML throughout the mine-life cycle, many of which have been incorporated into the TMM Project design and material management strategy (Figure 14 and Table 13).

The environmentally focused mine design has eliminated the features which are most often the cause of long-term ARD/ML issues at other mine sites:

- **No Open Pit**: Resource development would be by underground mining as opposed to open pit. The environmental benefits of underground mining, as compared to an open pit, include reduced land disturbance and waste generation and the avoidance of a pit lake or other large surface feature at closure.
- **No Waste Rock Stockpiles**: During operations, all waste rock would remain underground as backfill. The Project would not generate any permanent or even long-term surface stockpiles.
- **No High-Sulfur Tailings:** By design, because virtually all of the sulfide minerals are removed in the concentration process, the sulfur content of the tailings would be low (≤0.2%), which is below the threshold identified for acid generation. Storage in a dry stack facility, as opposed to a traditional slurry impoundment, is current industry best practice.

Additional ARD/ML prevention measures and engineering controls include:

- **Short-Term Ore Storage on Surface:** During operations, most ore would be stored in the Primary Ore Stockpile, a covered facility with a concrete floor. The Secondary Ore Stockpile, a lined facility, would be used intermittently. For both ore stockpiles, the duration of ore storage on surface would be very short (i.e. days) prior to processing.
- **Water Management**: All surficial contact water would be captured to prevent its discharge to the environment. Liners would be used to prevent a pathway for mine influenced water to the receiving environment.

# Signature Page

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# Tables

**Table 1: Geologic Model Units**

| | | Unit and Description | Acronym |
|---|---|---|---|
| Hanging Wall | South Kawishiwi Intrusion (SKI) | **Anorthositic troctolite to troctolite (ATA Series)**: Medium to coarse-grained, homogenous, well-foliated and locally layered troctolitic anorthosite to troctolite, and ophitic troctolitic rocks. | ATA |
| | | **Augite-bearing troctolite (Main AGT):** Homogeneous, coarse-grained subophitic to ophitic, poorly-foliated augite troctolite characterized by scattered augite-rich pegmatitic clots and patches. | AGT |
| | | **Pegmatoidal Unit (PEG):** Upper portion of the BMZ. Characterized by its larger grain size relative to the remainder of the BMZ. Although genetically related to the BMZ, this unit is almost always barren. | PEG |
| Ore Zone | | **Sulfide-bearing troctolite (BMZ - basal mineralized zone):** Heterogeneous, sulfide-bearing, vari-textured melatroctolite, troctolite, augite troctolite, anorthositic troctolite, and olivine gabbro with approximately 1 - 5 wt.% disseminated sulfides. The lower portion of the SKI and subdivided into four units: Upper Heterogenous Zone (UH); Stage 3 Melatroctolite (S3); Stage 2 Troctolite (S2); and, Stage 1 Troctolite/Anorthosite/Gabbro (S1). | BMZ |
| Hanging Wall | Xenoliths in the SKI | **Anorthositic Series (AN Series):** A mega-inclusion present in the eastern portion of the Maturi deposit. Composed of well-foliated anorthosite, troctolitic anorthosite, poikilitic troctolitic anorthosite, gabbroic anorthosite, and rarely gabbro and troctolite. | ANS |
| | | **Basaltic hornfels (Upper Basalt):** Fine-grained, granoblastic to poikiloblastic basaltic hornfels, containing variable amounts of plagioclase, augite, olivine, hypersthenes, and pigeonite. Commonly associated with Anorthosite xenoliths. | UPB |
| | | **Anorthositic gabbro to gabbro (Upper Gabbro):** A mixed group of Anorthositic Series rocks that occur in the central portion of the Project and include well-foliated anorthositic gabbro, gabbro, anorthosite, hornfelsed basalt, and augite troctolite. | UPG |
| Footwall | | **Porphyritic quartz monzonite (GRB - Giants Range Batholith):** Pink, coarse-grained, hornblende-phyric, quartz monzonite to diorite commonly with large orthoclase phenocrysts. It is strongly recrystallized and partially melted locally along the contact with the SKI. Locally mineralized and subdivided into three units: nickel-rich (G_N); disseminated (G_M); and, barren (G_B). | GRB |

Note:
SKI - South Kawishiwi Intrusion

**Table 2: MDNR Research Summary**

| Parameter | Study 1 | Study 2 | Study 3 | Study 4 | Study 5 |
|---|---|---|---|---|---|
| **Reference** | Lapakko and Antonson (1992) | Kellogg et al (2014) | Lapakko et al. (2013a) | Lapakko (1994) | Lapakko et al. (2013b) |
| **Scale** | Laboratory | Laboratory | Laboratory | Field | Laboratory |
| **Material Type** | Waste Rock | Waste Rock | Waste Rock | Low-grade ore | Tailings |
| **Test Type** | MDNR Reactor | MDNR Reactor | MDNR Reactor and Humidity Cell (ASTM 2007) | Stockpile | MDNR Reactor and Humidity Cell (ASTM 1996) |
| **No. Samples** | 16 | 15 | 17 | 6 | 8 |
| **Sulfur Content** | 0.18 to 3.12% | 0.18 to 1.64% | 0.07 - 1.36% | 0.63 - 1.41% | 0.20 wt.% (>90% present as sulfide) |
| **Test Duration** | 150 weeks | 78 to 1,252 weeks (24 years) | 8 years | 12 to 14 years | 10 years |
| **Bulk NP** | - | 12 - 21 kg $CaCO_3$/t | - | - | 14 - 19 kg $CaCO_3$/t |
| **Carbonate NP** | - | 0.7 - 2.5 kg $CaCO_3$/t | 1.6 - 4.8 kg $CaCO_3$/t | - | <1.1 kg $CaCO_3$/t |
| **Sample Source** | Blast holes at the Dunka mine (South Kawishiwi Intrusion) | Blast holes at the Dunka mine (South Kawishiwi Intrusion) | Babbitt and Dunka Road prospects of Partridge River intrusion | AMAX test stockpiles | Babbitt prospect of Partridge River intrusion |
| **Sulfide Occurrence** | Pyrrhotite dominant sulfide mineral in the samples | Pyrrhotite > chalcopyrite > cubanite > pentlandite (lesser amounts of Co and Zn sulfides) | - | Pyrrhotite > chalcopyrite / cubanite > pentlandite (Pile #1 sample) | pyrrhotite (65%) chalcopyrite (25%) pentlandite (10%), |
| **Notes** | | Continuation of 1992 study | | | Only chalcopyrite identified during microprobe analysis |

Note:
"-" Not applicable or not provided in paper.

**Table 3: Comparison of Standard HCT and MDNR Reactor**

| Parameter | HCT | MDNR Reactor |
|---|---|---|
| Sample Mass | 1 kilogram | 75 grams |
| Particle Size | < 1/4 inch (6.35 mm) | 0.053 to 0.149 mm diameter |
| Leach Volume | 500 or 1,000 mL | 200 mL |
| Leach Cycle Duration | weekly | weekly |
| Solution to Solid Ratio | 0.5 : 1 or 1 : 1 | 2.7 : 1 |

**Table 4: MDNR Long-Term Study Details**

| | Study 1 | | | Study 2 | | |
|---|---|---|---|---|---|---|
| | Sulfur (wt.%) | Minimum pH | Test Duration (weeks) | Sulfur (wt.%) | Minimum pH | Test Duration (weeks) |
| Group 1 | 0.18 – 0.40 | 6.1 – 6.4 | 150 | 0.18 ≤ %S ≤ 0.22 | 5.7 – 5.9 | 1252 |
| Group 2 | 0.41 – 0.71 | 4.8 – 5.3 | 150 | 0.40 ≤ %S ≤ 0.70 | 3.8 – 4.1 | 441 - 909 |
| Group 3 | 1.12 – 1.64 | 4.3 – 4.9 | 69 | 0.70 < %S ≤ 1.64 | 3.0 – 3.5 | 360 - 724 |
| Group 4 | 2.06 – 3.12 | 3.5 – 4.2 | 78 | N/A | N/A | N/A |

Notes:
Study 1: Lapakko and Antonson (1992)
Study 2: Kellogg et al. (2014)
N/A - Not applicable

**Table 5: Tailings Characteristics (10-year MDNR Study)**

| Parameter | Value |
|---|---|
| Total Sulfur | 0.2 wt.% |
| Sulfide Distribution | pyrrhotite (65%)<br>chalcopyrite (25%)<br>pentlandite (10%) |
| Sulfide Liberation | 87% |
| Bulk Neutralization Potential (NP) (Sobek et al. 1978) | 14 - 19 kg $CaCO_3$/t |
| Carbonate NP | 1.1 kg $CaCO_3$/t |
| Paste pH | 8.29 |

Note:

Source: Lapakko et al. (2013b)

**Table 6: PolyMet EIS Waste Rock Classification**

| Class | Sulfur Content (wt.%) | % Waste Rock Mass | ARD Potential |
|---|---|---|---|
| 1 | ≤0.12 | 70% | Low |
| 2 | 0.12 < %S ≤0.31 | 24% | Low to Medium |
| 3 | 0.31 < %S ≤0.6 | 3% | Medium |
| 4 | > 0.6 %S (Duluth Complex) | 3% | High |
| | 0.4 ≤ %S ≤ 5.0 (Virginia Formation)[(a)] | | |

Notes:

[(a)] Virginia formation not applicable to the Maturi deposit as it does not occur there.

Source: Table 3.2-8 (MDNR 2015)

**Table 7: Silicate Mineral Neutralization Potential Values**

| Mineral | Neutralization Potential (NP) (kg $CaCO_3$/t) | Note |
|---|---|---|
| Olivine | 38 | |
| Plagioclase Feldspar | <1 - 14 | Dependent on the amount of anorthite (calcium end-member - $CaAl_2Si_2O_8$) |
| Pyroxene | 4.6 | |

Note:
Data source: Jambor et al. 2007

**Table 8: Sulfide Mineral Reactivity**

| Mineral | Formula | Acid Generation Potential (Plumlee 1999) | |
|---|---|---|---|
| | | Acid Generating | Resistance to Oxidation |
| Bornite | $Cu_5FeS_4$ | (a) | Medium to High |
| Chalcopyrite | $CuFeS_2$ | (b) | Medium to High |
| Cubanite | $CuFe_2S_3$ | (c) | |
| Pentlandite | $(Ni,Fe)_9S_8$ | (b) | |
| Pyrrhotite | $Fe_{1-x}S$ | (a) | Low |

Notes:

(a) Known to generate acid with oxygen as the oxidant (Plumlee 1999).

(b) May generate acid with ferric iron as the oxidant (Plumlee 1999).

(c) Inferred as unlikely to generate acid with oxygen as the oxidant based on metal/sulfur ratio ≥ 1.

**Table 9: Mine Materials Characterization Testing Program Components**

| Analysis | Test Method | Literature Reference |
|---|---|---|
| **Static Testing** | | |
| **Chemical Analysis** | | |
| Whole Rock | XRF (Borate Fusion) | - |
| Trace Metal | 4-Acid Digest (most metals)<br>3-Acid Digest (As, Sb, Se)<br>Aqua Regia Digest (Hg) | Rudolf 1979<br>USEPA 3052 (USEPA 1996)<br>USEPA 7471B (USEPA 2007) |
| **Mineralogical Analysis** | | |
| Bulk | x-ray diffraction (XRD)<br>QEMSCAN | - |
| Mineral Fibers | Transmission electron microscopy (TEM) | MDH 851 (MDH 1991)<br>MDH 852 (MDH Year Unknown) |
| **ARD Potential** | | |
| Acid Base Accounting (ABA) | Modified Sobek | Sobek et. al. 1978 (sulfur)<br>MEND 1991 (NP)<br>ASTM 2009 (carbon) |
| Net Acid Generation (NAG) Testing | EGi Method | AMIRA 2002 |
| **Short-Term Leach Testing** | | |
| Synthetic Precipitation Leaching Procedure (SPLP) | USEPA Method 1312 | USEPA 1994 |
| NAG Leachate | EGi Method | AMIRA 2002 |
| **Kinetic Testing** | | |
| Humidity Cell | ASTM D 5744-18 | ASTM 2018 |
| Monolith Diffusion Testing | USEPA Method 1315 | USEPA 2017 |
| Flooded Column | Project specific | none |

**Table 10: MMCP Sample Summary**

| Material Type | MMCP Samples | |
|---|---|---|
| | Static Testing | Kinetic Testing |
| Ore | 36 | 6 |
| Waste Rock | 193 | 29 |
| Tailings | 14 | 6 |

**Table 11: ARD Screening Guidelines for Mine Materials**

| Sample Potential | Criteria | Comments |
|---|---|---|
| PAG | NPR<1 | Potentially acid generating material, unless sulfide minerals are non-reactive, or NP is preferentially exposed on surfaces. |
| Uncertain | 1<NPR<2 | Possibly PAG if NP is insufficiently reactive or is depleted at a faster rate than sulfides. |
| NPAG | NPR>2 | Non-potentially acid generating material, unless NP is insufficiently reactive, extremely reactive sulfides are present, or preferential exposure of sulfides is found in the material. |

Notes:

Source: MEND 2009

NP = neutralization potential

AP = acid generation potential

PAG = potentially acid generating

NPAG = non-potentially acid generating

NPR = neutralization potential ratio (NP/AP)

**Table 12: PolyMet and TMM Waste Rock Management Comparison**

| | TMM | PolyMet | | |
|---|---|---|---|---|
| | **Construction Period Rock** | **Class 1** | **Class 2/3** | **Class 4** |
| Material Type | Waste Rock and Ore | Waste Rock | Waste Rock | Waste Rock |
| Approximate Tonnage (MT) | 1.1 | 152.3 | 39.9 | 5.6 |
| $S_{TOT}$ (wt.%) | > 0.1 | < 0.12 | 0.12 to 0.6 | > 0.6 |
| Surface Facility Footprint (acres) | 11 | 526 | 180 | 57 |
| Surface Facility Height (feet) | 80 | 240 | 160 | 80 |
| Time on Surface (years) | 3.5 (max) | Permanent | 20 (max) | 11 (max) |
| Relocation | Processed through Mill | Not applicable | Moved to pit | Moved to pit |
| Design Includes a Liner | Yes | No | Yes | Yes |

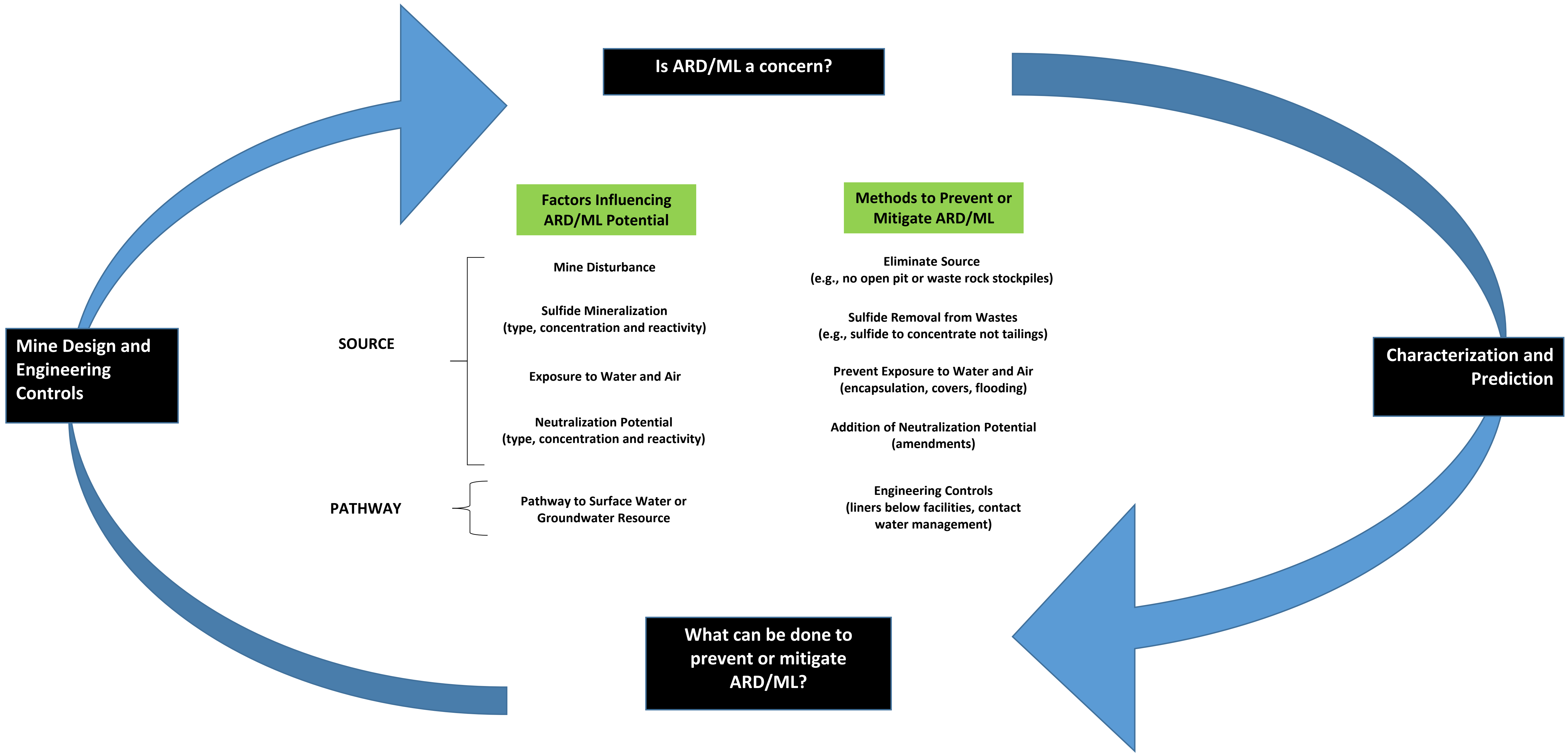
Note:

PolyMet Source: Table 3.2-7 (MDNR 2015)

**Table 13: Twin Metals Minnesota ARD Prevention and Mitigation Measures**

| ARD Prevention / Mitigation Measure (INAP 2012) | Material Type / Location | | | |
|---|---|---|---|---|
| | Tailings (Dry Stack Facility and Underground Backfill) | Waste Rock Surface Stockpile | Ore Surface Stockpile | Underground (Sulfide Mineral Exposures) |
| Minimize disturbance | Approximately 40% of tailings returned to underground as backfill | Small tonnage of waste rock and ore stored temporarily on surface (~1.1 MT) during construction and first two years of operation | Small tonnage of waste rock and ore stored temporarily on surface (~1.1 MT) during construction and first two years of operation | Underground mining (as opposed to open pit)<br><br>Mine design to limit damage from blasting and mine induced stresses |
| Minimize oxygen supply | Compacted placement of filtered tailings in 1-m lifts, short period of exposure for each lift (weeks to months)<br><br>Progressive reclamation during operations (vegetated soil cover) | Short-term (<4 years) storage on surface | Short-term storage on surface:<br><br><4 years for ore mined during construction<br><br>Days for ore mined during operations (ore crushed underground) | Placement of backfill during mining<br><br>Encapsulation of waste rock in cemented tailings backfill<br><br>Flooding of underground workings at closure |
| Minimize water infiltration and leaching (water acts as both a reactant and a transport mechanism) | Filtered tailings to limit process water entrainment<br><br>Surface disposal - lined facility with grout curtain to prevent leakage to groundwater, surface compaction to reduce permeability<br><br>Underground disposal - Reduction in permeability due to addition of binder to cemented tailings backfill | Lined facility | Lined facility (construction)<br><br>Covered facility with concrete floor (operations) | Operations - capture and manage contact water<br><br>Closure - little to no groundwater movement after flooding |
| Minimize, remove, or isolate sulfide minerals | Virtually all sulfur reports to concentrate | PAG development rock stored temporarily on surface will be milled within first two years of operation | | |
| Control pore water solution pH | | | | Use of cemented backfill<br><br>Mixing with groundwater inflow (source of alkalinity) |
| Maximize availability of acid neutralizing minerals and pore water alkalinity | Neutralization potential (NP) available due to grain size reduction | | | Placement of cemented tailings backfill (amendments provide some, albeit typically limited, NP) |

# Figures

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MINE MATERIALS CHARACTERIZATION PROGRAM

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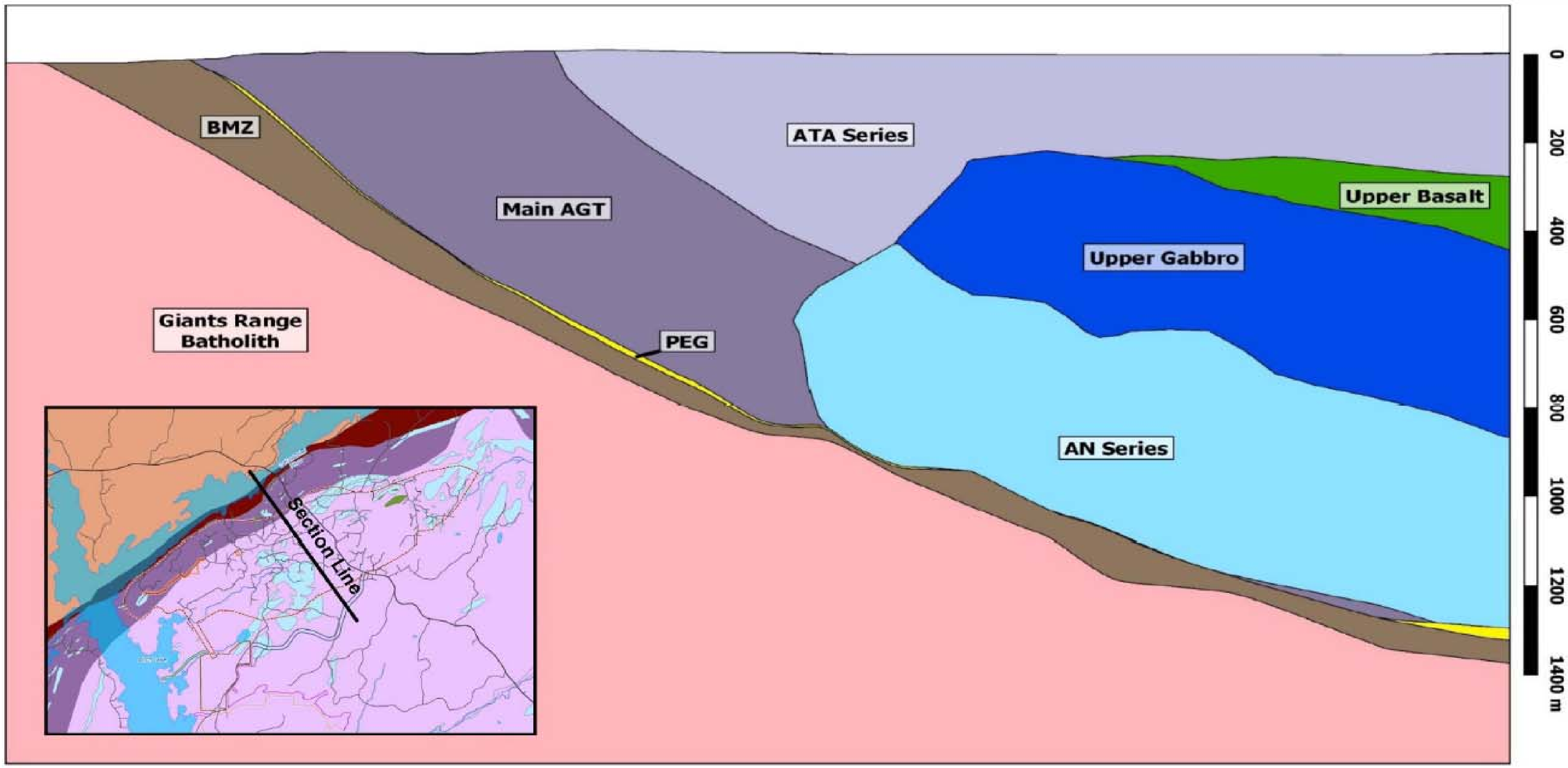
TITLE
**ARD/ML Identification and Prevention / Mitigation Approach**

| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 1 |




**NOTES:**
1. Bedrock geology is an compilation of public and proprietary data sets.
2. Hydrographic data from Minnesota Department of Natural Resources.
3. Horizontal datum based on NAD 1983. Horizontal coordinates based on Minnesota State Plane North (feet).

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TITLE
**Maturi Deposit Example Cross Section**
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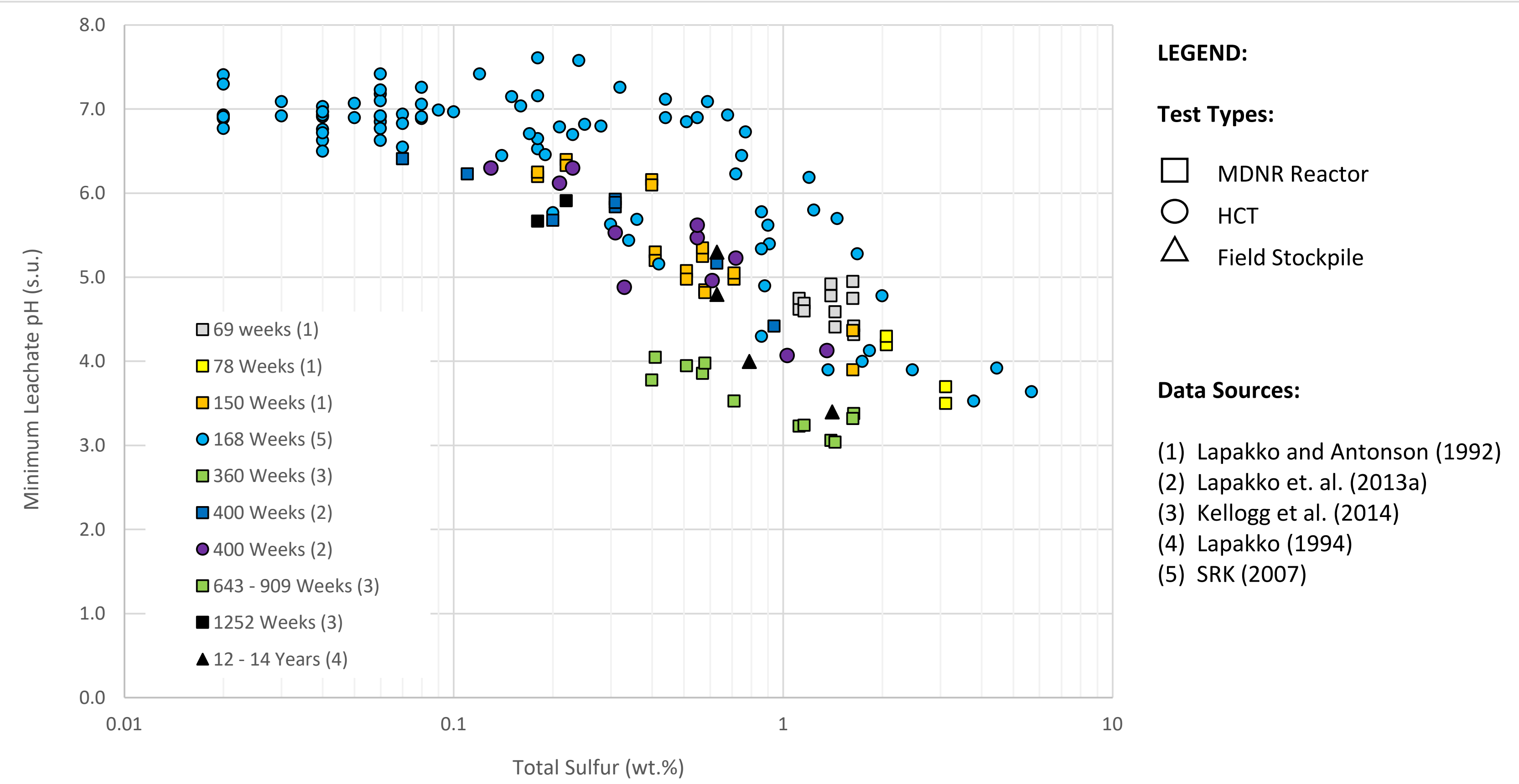
| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 2 |




Series names indicate test duration and identify data source
(i.e. number in parentheses refers to data sources list to right of figure)

| | |
|---|---|
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| CONSULTANT<br>GOLDER MEMBER OF WSP | TITLE<br>**MDNR Duluth Complex Kinetic Testing Results** |

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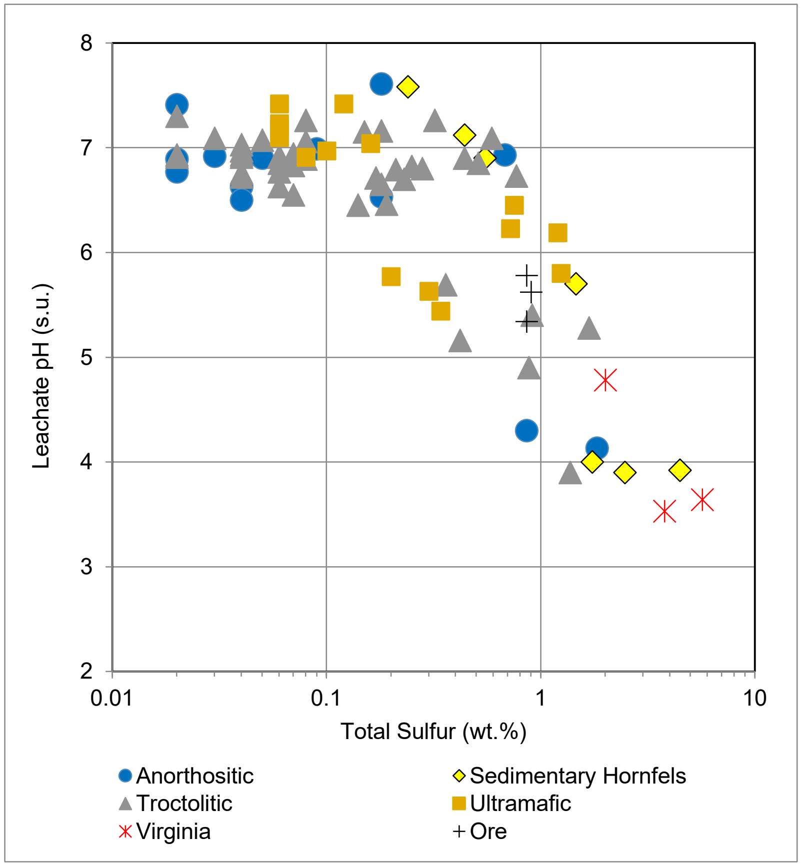


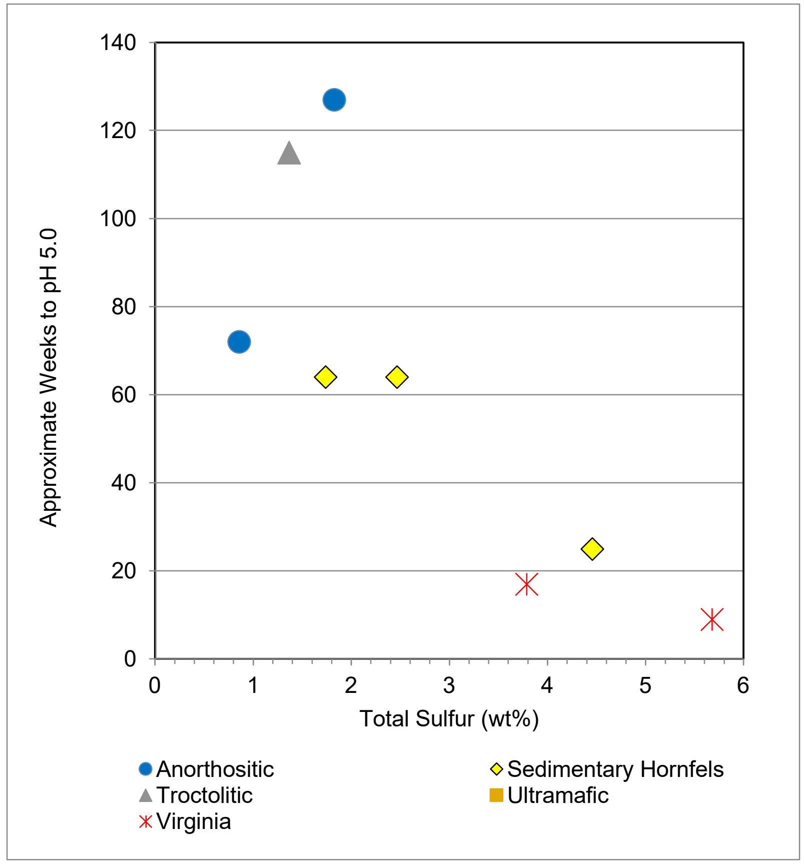


Data Source: SRK 2007

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TITLE
**PolyMet NorthMet Deposit - Kinetic Testing Results**
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| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 4 |

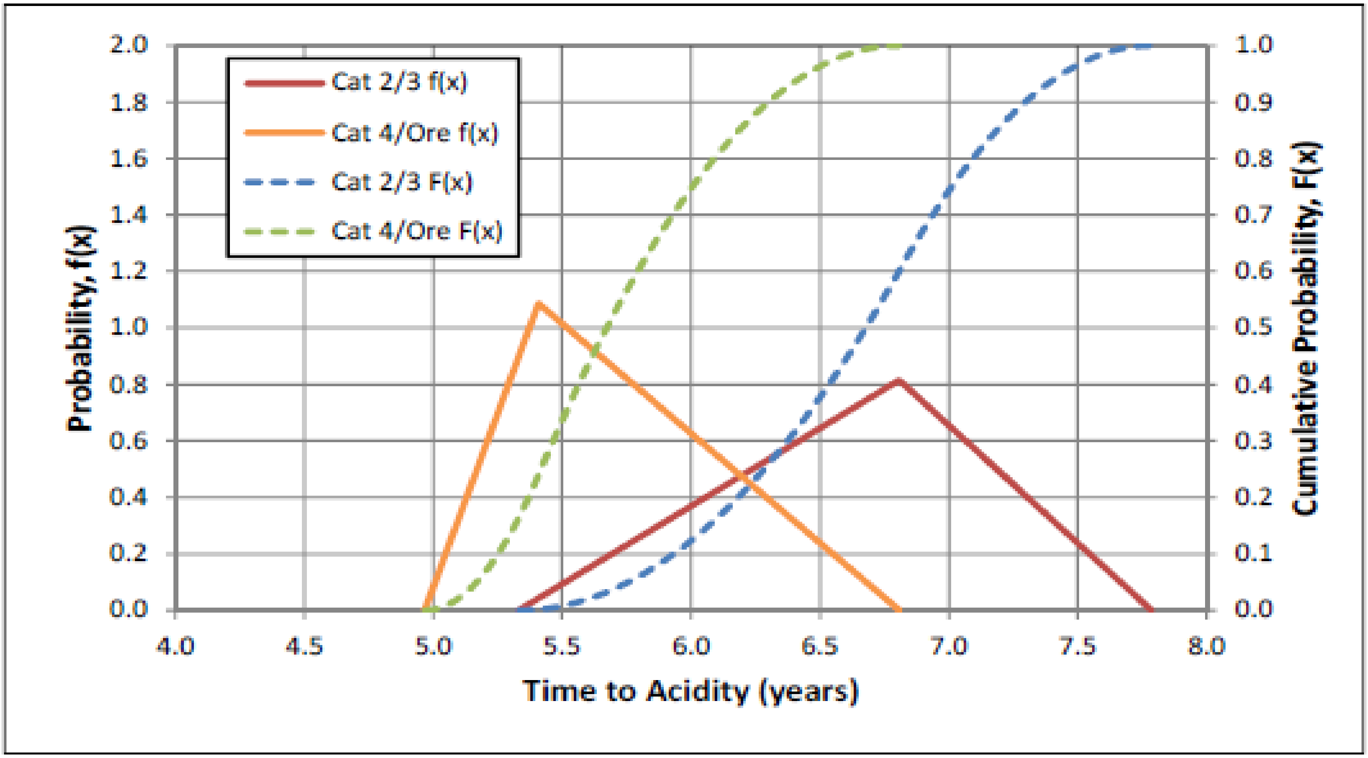


**Figure 8-13 Distributions for the Time to Onset of Acidity**

Predicted distributions for the onset to acidity (Figure 8-13 in source document)

Reproduced from PolyMet 2015

| | | | |
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| | | PROJECT NO.: 113-93664-20 | CONTROL: . / REV.: 0 / FIGURE: 5 |

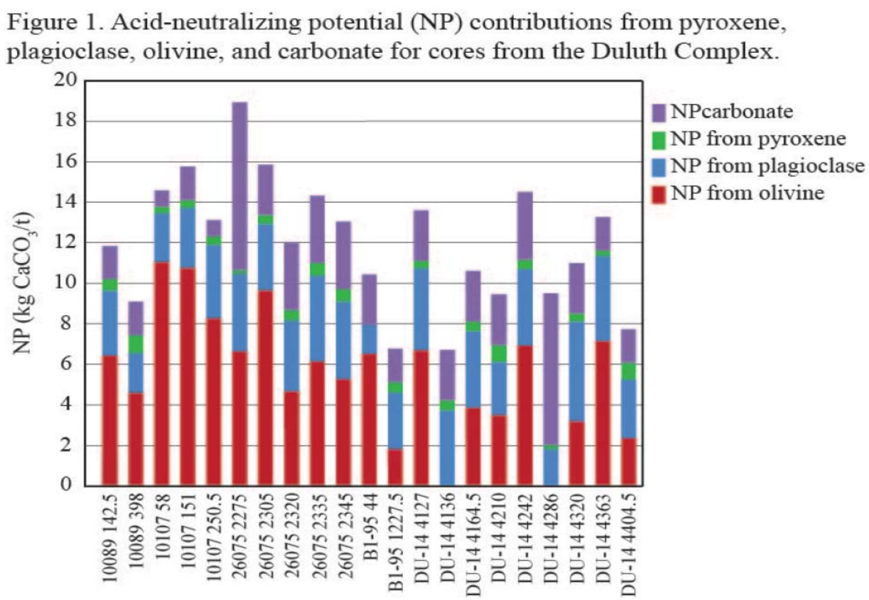


**Figure 5A**

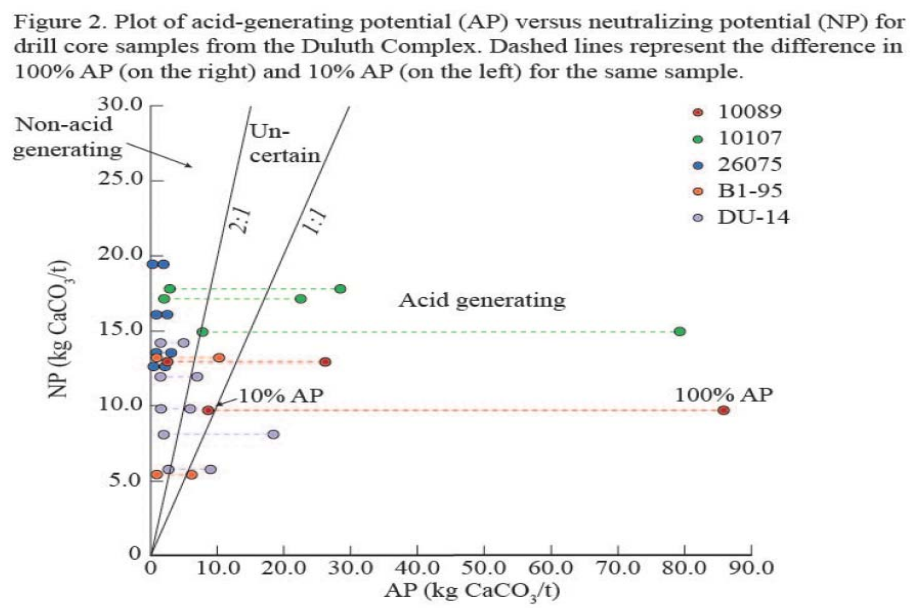


**Figure 5B**

Reproduced from Schulte et al. 2016

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TITLE
**Silicate NP (Schulte et al. 2016)**
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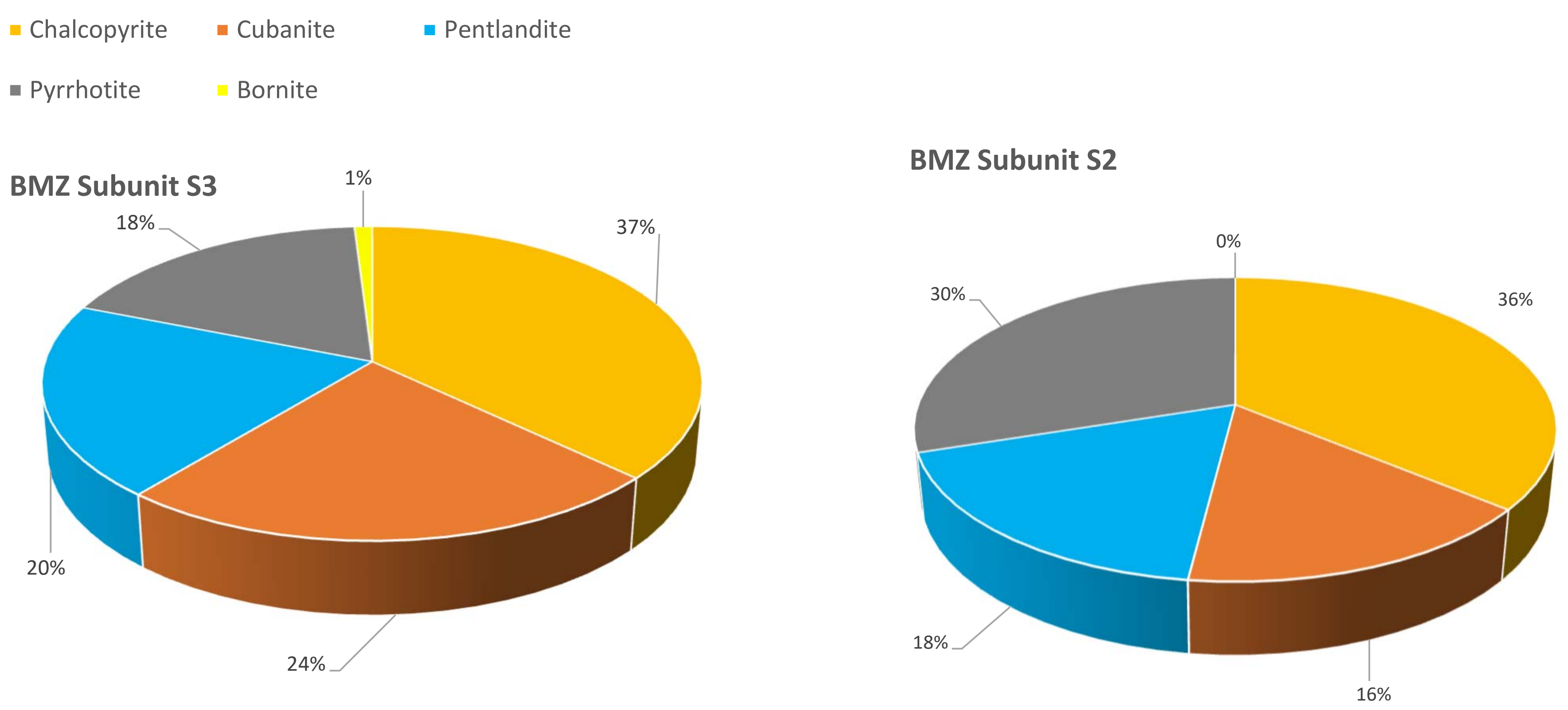
| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 6 |

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TITLE
**S3 and S2 Characteristic Sulfide Mineral Distribution**
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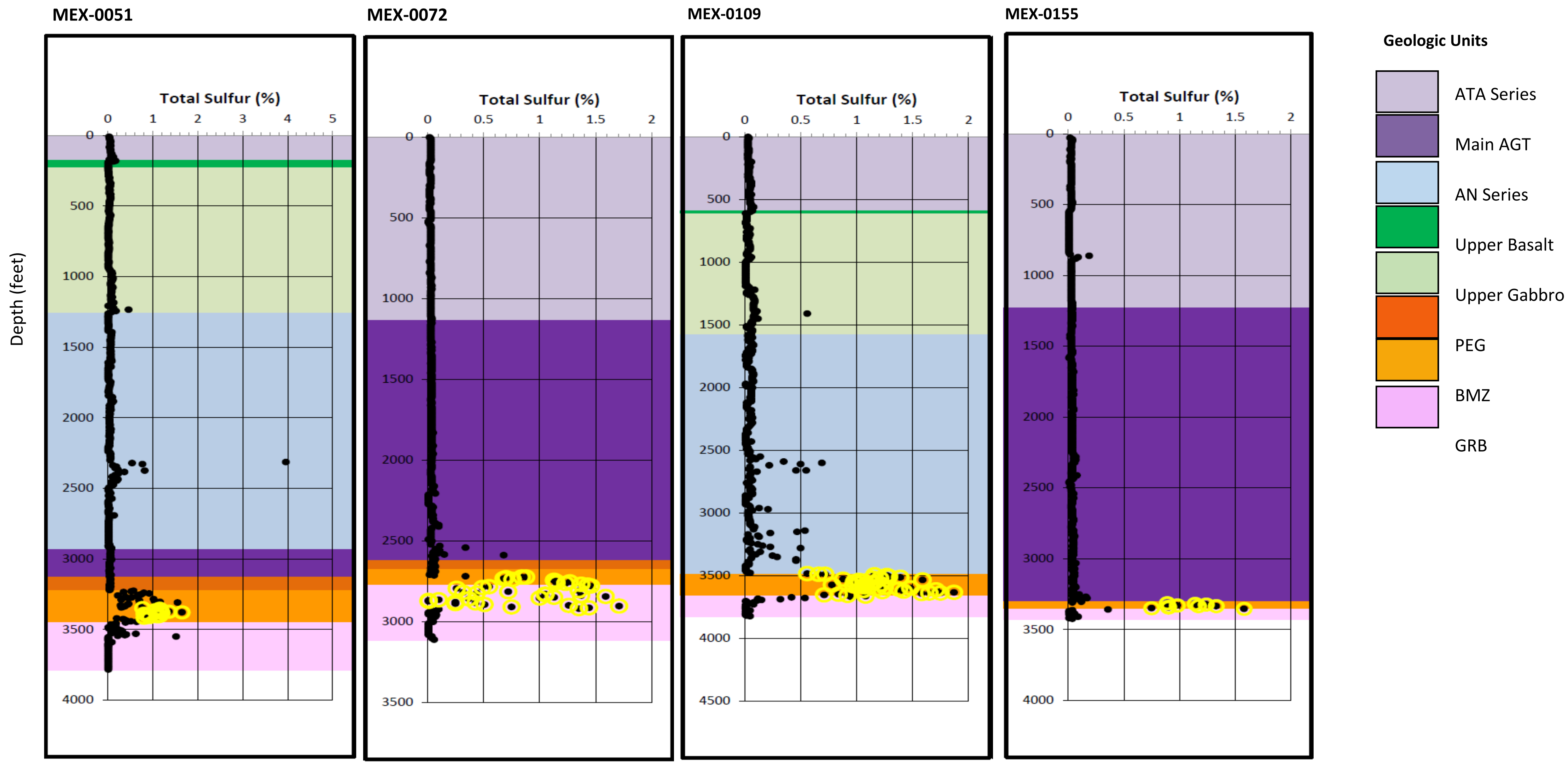
| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 7 |

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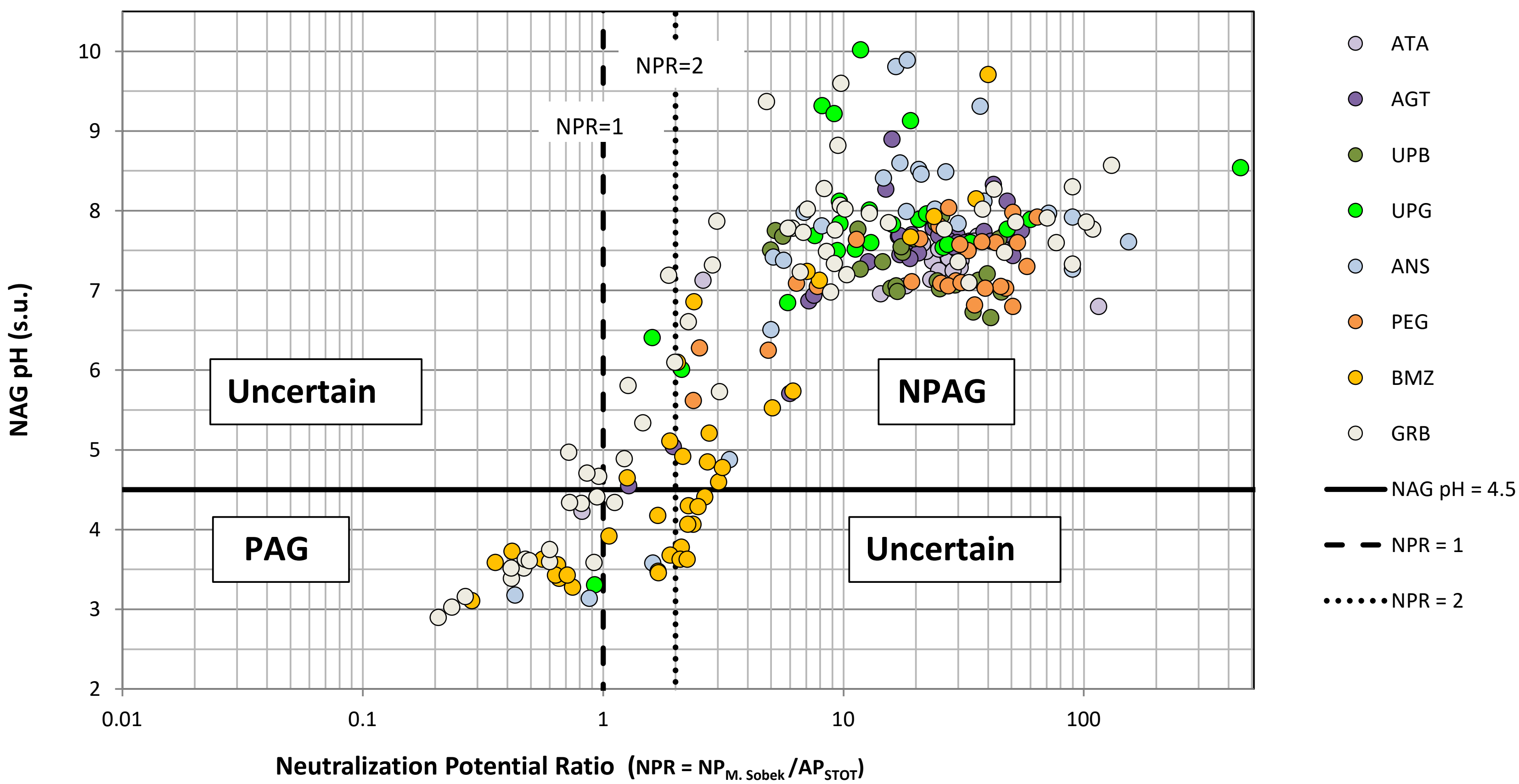
TITLE
**Maturi Drill Core Total Sulfur Data**

| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 8 |




Note(s):
ARD Potential Classification: PAG - potentially acid generating; Uncertain; and, NPAG - non-potentially acid generating

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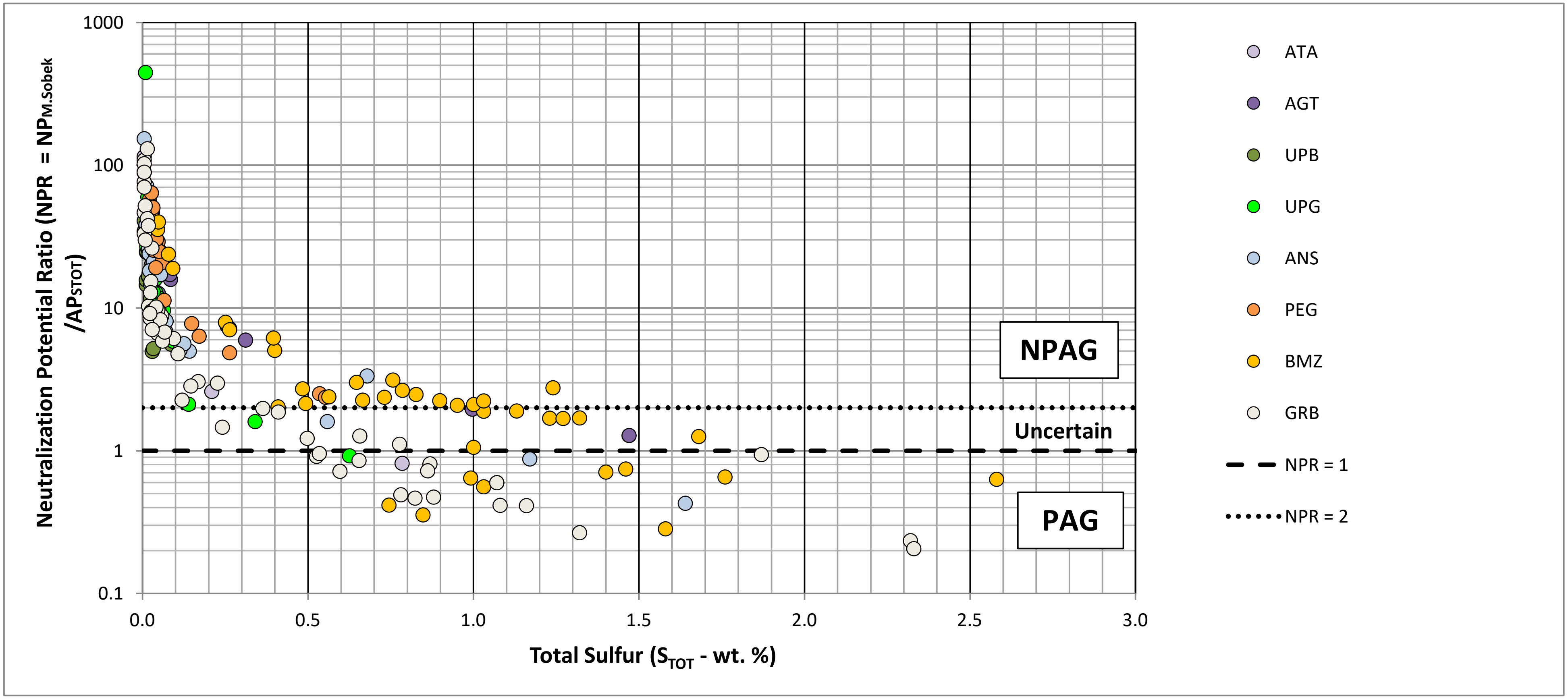
TITLE
**ARD WHITE PAPER**
**Waste Rock and Ore**
**Neutralization Potential Ratio vs. NAG pH**

| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 9 |




Note(s):

Non-detect concentrations shown at the reporting limit.

ARD Potential Classification: PAG - potentially acid generating; Uncertain; and, NPAG - non-potentially acid generating

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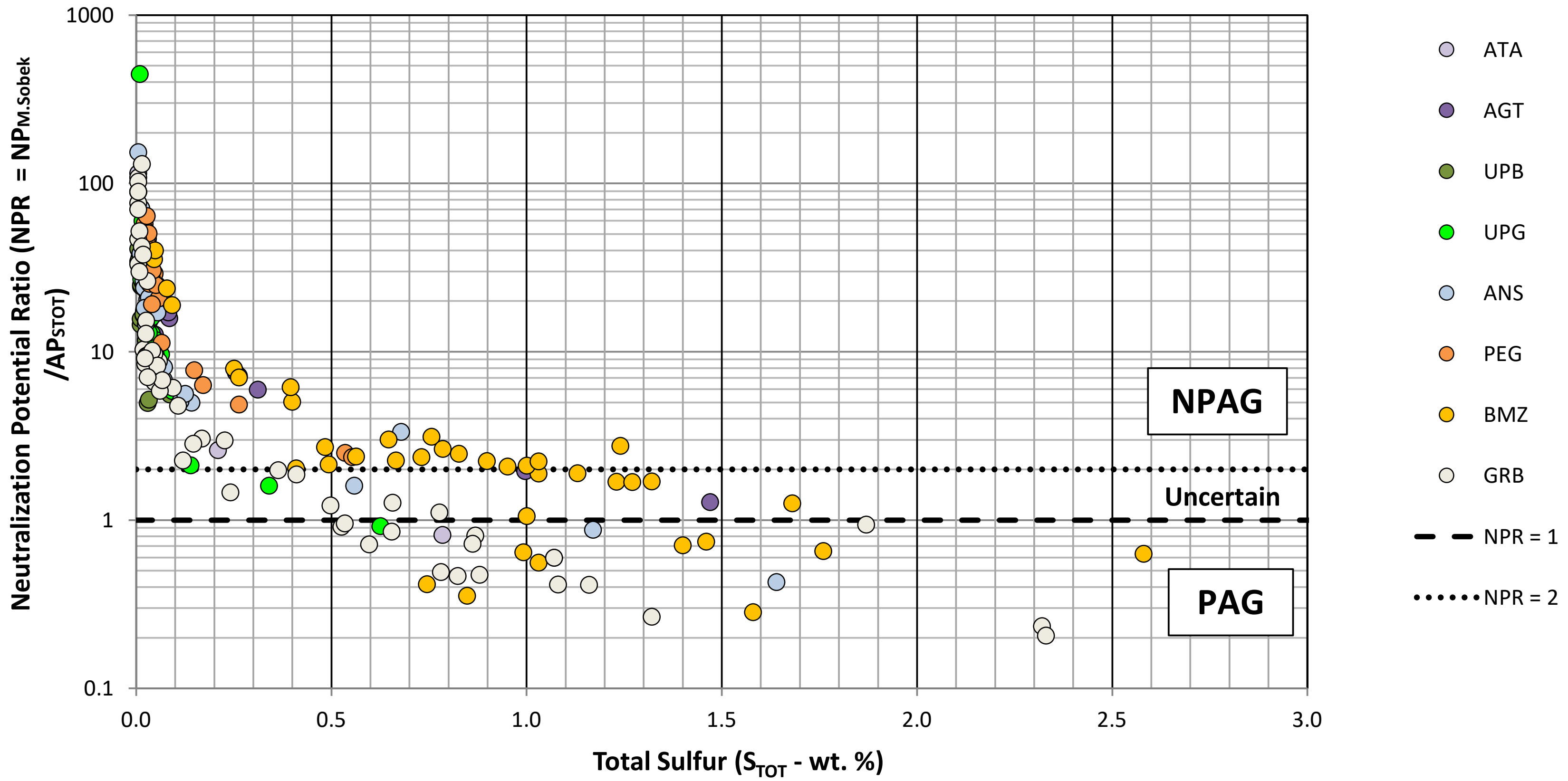
TITLE
**ARD WHITE PAPER**
**Waste Rock and Ore ABA**
**Total Sulfur vs. Neutralization Potential Ratio**

| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 10 |




Note(s):
Non-detect concentrations shown at the reporting limit.
ARD Potential Classification: PAG - potentially acid generating; Uncertain; and, NPAG - non-potentially acid generating

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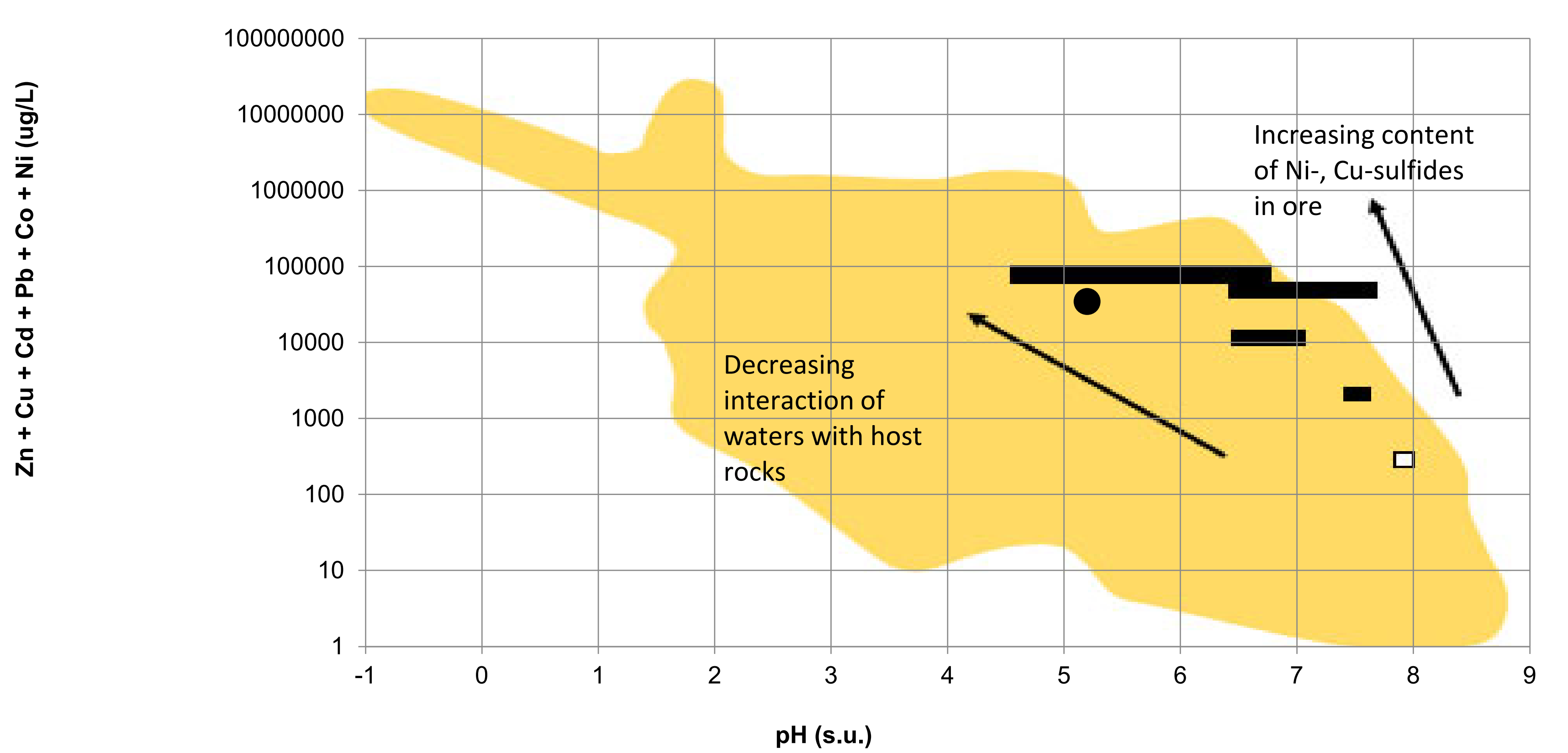
| | REVIEWED | CR | PROJECT NO. 113-93664-20 · CONTROL . · REV. 0 · FIGURE 10 |
| | APPROVED | MB | |




Note: Figure reproduced from Plumlee et al. (1999). Measured data are approximate (visually reproduced on graph).

Legend

- ● Duluth Complex
- ■ Other Duluth samples
- □ Stillwater
- All deposit types, Appendix

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TITLE
**FICKLIN DIAGRAM**

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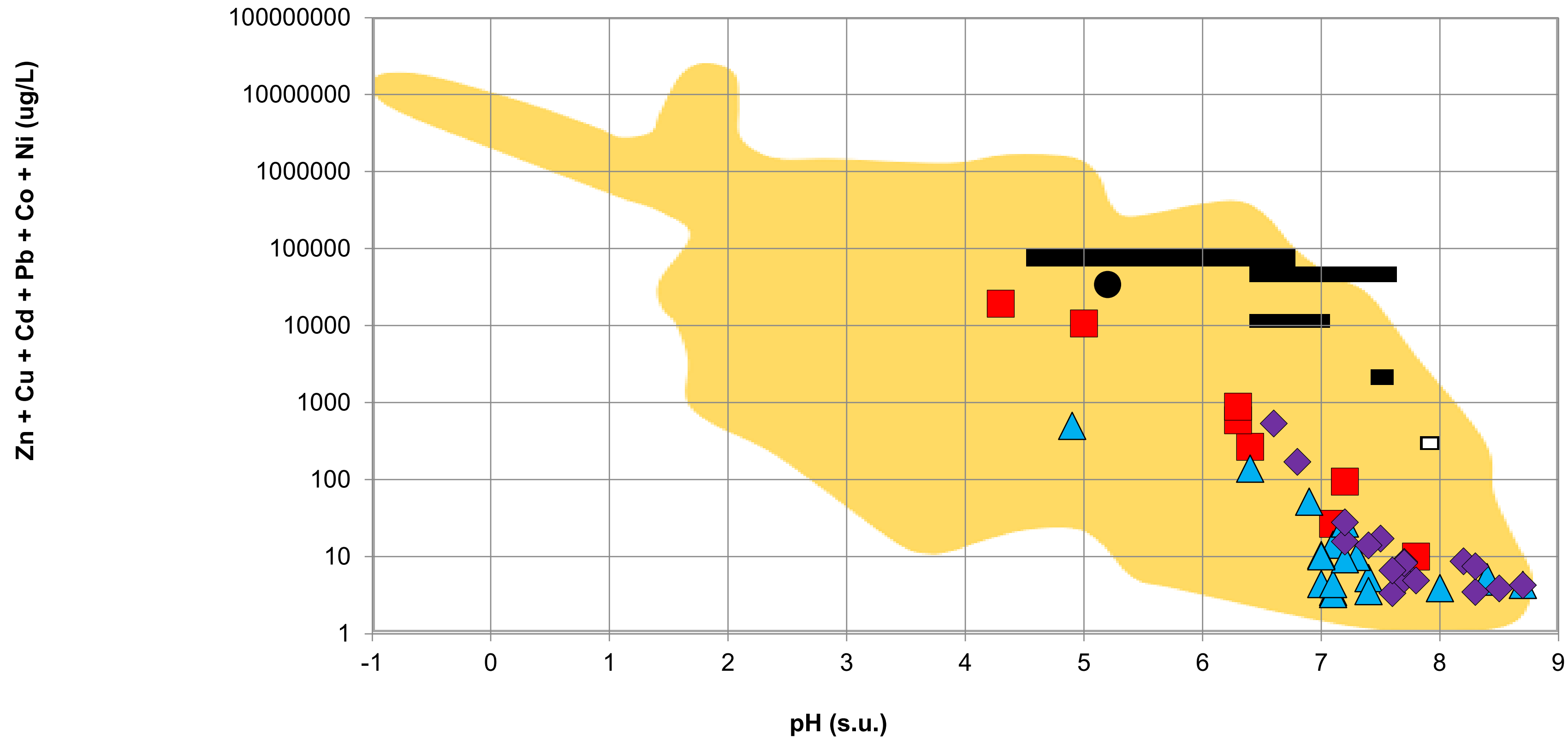
| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 11 |




Notes: Leachate results from MMCP humidity cell testing program shown on Ficklin diagram.
Humidity cell testing non-detect concentrations assumed equal to the analytical reporting limit in calculation of metals concentration (y-axis).
All other deposits shown as orange shading from Plumlee et al. (1999).

Legend

- Ore (Week 116)
- Hanging Wall Waste Rock (Week 92)
- Footwall Waste Rock (Week 92)
- Duluth Complex, Plumlee et al. (1999)
- Other Duluth Samples, Plumlee et al. (1999)
- Stillwater, Plumlee et al. (1999)
- All deposit types - Appendix, Plumlee et al. (1999)

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TITLE
**SITE-SPECIFIC FICKLIN DIAGRAM - WASTE ROCK AND ORE**
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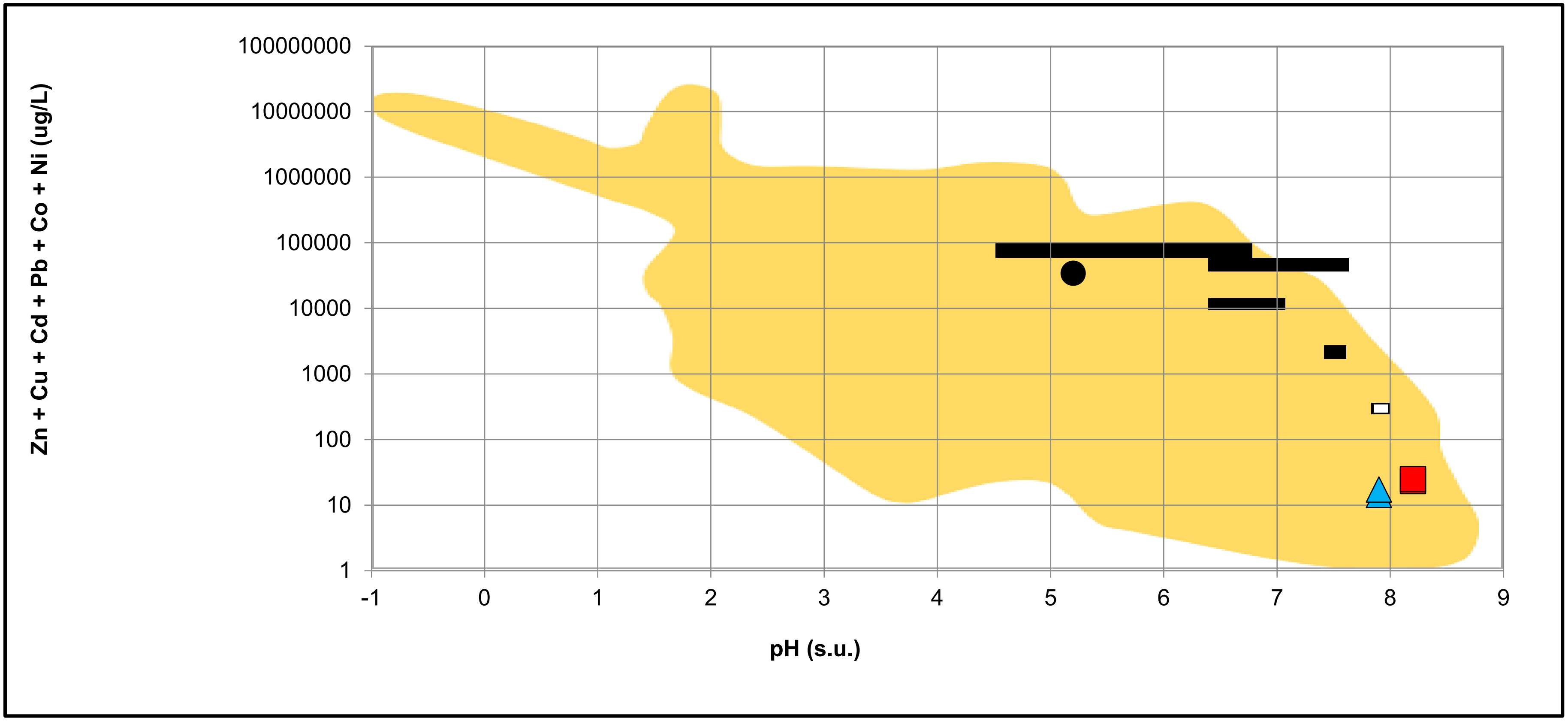
| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 12 |




Notes: Leachate results from MMCP humidity cell testing program shown on Ficklin diagram.
Humidity cell testing non-detect concentrations assumed equal to the analytical reporting limit in calculation of metals concentration (y-axis).
All other deposits shown as orange shading from Plumlee et al. (1999).

Legend

- ■ Cemented Tailings (Week 72)
- ▲ Whole Tailings (Week 72)
- ● Duluth Complex, Plumlee et al. (1999)
- ■ Other Duluth Samples, Plumlee et al. (1999)
- □ Stillwater, Plumlee et al. (1999)

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| APPROVED | MB |

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TITLE
**SITE-SPECIFIC FICKLIN DIAGRAM - TAILINGS**
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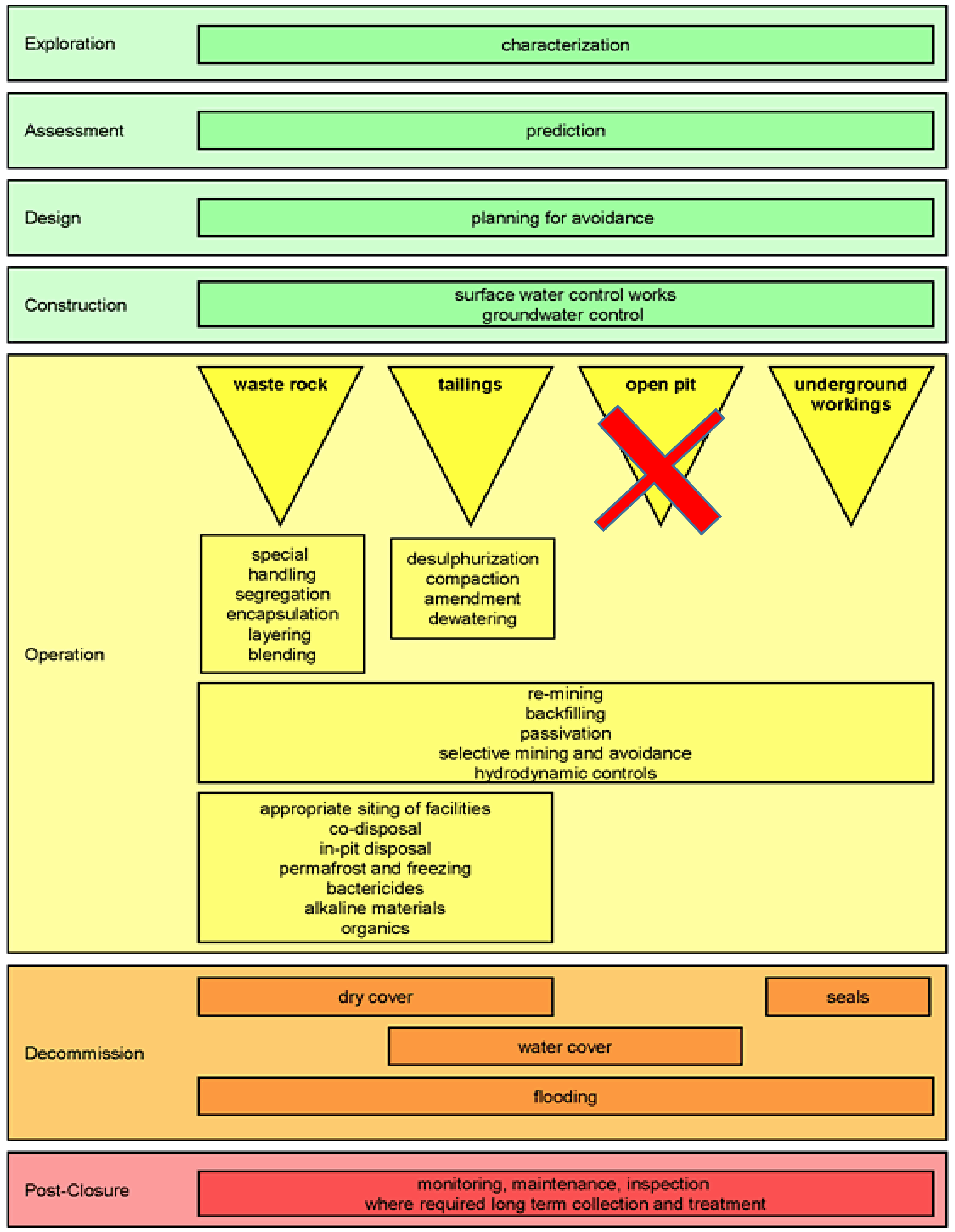
| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 13 |

## GARD Guide - Methods of Prevention and Mitigation of ARD




Source: Figure reproduced from the GARD Guide (Figure 6-5, INAP 2014)

## TMM Project Methods of Prevention and Mitigation of ARD

**Characterization:** Extensive geochemical and receiving environment characterization (ongoing)

**Prediction:** Multi-disciplinary baseline and impact assessment modeling (ongoing)

**Avoidance:** No open pit, no long-term waste rock stockpiles

**Surface Water and Groundwater Control:** Contact water management, diversion of non-contact water, liners below mine facilities, grout curtain below dry stack facility

**Waste Rock:**
- Underground (vs. open pit) resource development to minimize volume of waste rock
- Only construction phase waste rock brought to surface
- No long-term waste rock stockpiles on surface (all waste rock used for construction or processed through the Mill)

**Tailings:**
- Non-acid generating low sulfur tailings (<0.2 wt.% sulfur) stored in a dry stack facility or used as backfill
- Surface disposal - lined facility with grout curtain to prevent leakage to groundwater, placed in 1-m lifts and compacted to limit water and oxygen ingress

**Underground:**
- Mine design to limit damage from blasting and mine induced stresses
- Placement of backfill within stopes during mining

**Tailings:**
- Progressive reclamation and placement of cover

**Underground:**
- Fully flooded at closure, little to no groundwater movement

**Monitoring:** Prescribed within permits

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TITLE
**Twin Metals Minnesota ARD Prevention and Mitigation Measures**

| PROJECT NO. | CONTROL | REV. | FIGURE |
|---|---|---|---|
| 113-93664-20 | . | 0 | 14 |

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