Guidance Manual

MnDOT Guidance Manual for Potentially Acid Generating Materials in Northern Minnesota

Authors: K. Eisen, M. Blair, D. Levitan, S. Theriault, W. Swanson

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This manual provides guidance for methods of evaluating projects to assess the potential of encountering acid-generating materials in northern Minnesota. Methods for field reconnaissance, preliminary testing, characterization sampling efforts, interpretation of results, approaches for mitigation, and approaches for project monitoring are included.

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FINAL REPORT

Prepared by:

K. Eisen
M. Blair
D. Levitan
S. Theriault
W. Swanson
Barr Engineering Co.

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Jason Richter, MnDOT

Michael Kalnbach, MnDOT

Dan Squires, MnDOT

Robert Edstrom, MnDOT

Micah Holzbauer, MnDOT

Zach Wenz, Minnesota Department of Natural Resources

Dean Peterson, Natural Resources Research Institute

John Heine, Natural Resources Research Institute

George Hudak III, Natural Resources Research Institute

Rens Verburg, Golder Associates

Mehgan Blair, Barr Engineering Co.

PREFACE

Awareness of the potential environmental effects of disturbing sulfur-bearing materials has increased in Minnesota since the early 2000s. When sulfide-bearing materials are exposed to oxygen and moisture, they may begin to generate acid (unless otherwise mitigated), which causes additional dissolution and mobilization of metals into the environment. The acid generated can negatively affect the durability of pavements, structures and slopes, cause vegetative stress, and create water quality issues in surface waters and groundwater. Excavations that proceeded without scrutiny and may have exposed potentially acid-generating (PAG) materials are now undergoing extensive evaluations, particularly in northeastern Minnesota, to characterize and mitigate the potential effects prior to exhumation.

The recent experience of MnDOT re-aligning Trunk Highway 1/169 between Tower and Ely (termed the "Eagle's Nest" project) resulted in several phases of re-design, investigation, and the development of MnDOT's first repositories for PAG materials. During the design and investigation phases, it was recognized that a guidance document for MnDOT project personnel would benefit future MnDOT projects.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABA	acid-base accounting
AGP	acid-generating potential
AP	acid-generating potential
ARD	Acid Rock Drainage
CCE	calcium carbonate equivalent
CP	Characterization Plan
cy	cubic yards
DI	deionized
g	gram
Ga	giga-annum, one billion years ago
GAM	geotechnical asset map
GPS	global positioning system
HCl	hydrochloric acid
MDH	Minnesota Department of Health
MDNR	Minnesota Department of Natural Resources
mL	milliliter
ML/ARD	metals leaching/acid rock drainage
MnDOT	Minnesota Department of Transportation
MPA	Maximum Potential Acidity
MPCA	Minnesota Pollution Control Agency
MRR	Materials and Road Research
MWI	Minnesota Well Index
NAG	net acid generation
NAGpH	net acid generation pH
NNP	net neutralization potential
NP	neutralizing potential
NPR	net potential ratio
ORP	oxidation-reduction potential
PAG	potentially acid generating

PPT	Parts per thousand
QC	quality control
QP	qualified professional
RPD	relative percent difference
RQD	rock quality designation
SAM	supplemental alkaline material
SF	safety factor
T/kT	tons (of calcium carbonate equivalent) per kiloton (of material)
USCS	United Soil Classification System
XRD	X-ray diffraction

EXECUTIVE SUMMARY

This *MnDOT Guidance Manual for Potentially Acid-Generating Materials in Northern Minnesota* (PAG Guidance) was developed for the Minnesota Department of Transportation (MnDOT) to aid in project decision making. Projects, for the purpose of this PAG Guidance, are defined as construction or maintenance activities that have the potential to encounter and disturb potentially acid-generating (PAG) rock. This document provides a decision-making framework describing the process of screening, characterizing, evaluating, mitigating, and monitoring earth materials that are PAG. The methods and protocols presented in this PAG Guidance are based on decades of research and testing in the coal mining, hard rock mining, and transportation industries.

PAG materials found in Minnesota soil and bedrock typically contain sulfur-bearing minerals that, when exposed to oxygen and moisture, may form acidic runoff containing sulfate and metals. When present, these discharges can negatively impact resources and receptors such as surface water, groundwater, vegetation, and aquatic life. Environmental risks from PAG materials are a concern in Minnesota, particularly in northeastern Minnesota (MnDOT District 1), where many rock types have limited acid neutralization capacity. During natural weathering processes, the acid generation process decreases as exposed PAG surfaces are exhausted of reactive sulfur. However, construction projects that excavate and crush materials can renew, enhance, or initiate new acid generation processes by exposing fresh PAG materials to the atmosphere. In addition to environmental risks, acid generation within transportation settings has been responsible for structural failures due to corrosion and spalling, as well as geotechnical failures due to destabilization in slopes and fills.

Prior to design and construction, an evaluation will be performed to assess the likelihood of encountering PAG materials during rock excavations. Initial screening via a desktop study will be conducted using newly developed GIS layers showing top-of-bedrock and PAG risk within bedrock formations of northern Minnesota (Peterson, 2018) and additional resources. Depending on these results, the project may determine that no additional activities will be needed, a *de minimis* mitigation may be implemented, or a more thorough Characterization Program may be required. The Characterization Program would implement a variety of data collection and testing methods for determining the presence and quantity of PAG, uncertain, or non-PAG materials in the soil and rock. Surface and groundwater samples may also be acquired to establish baseline quality for comparison to post-construction monitoring measurements. If PAG materials will be encountered during excavations, then a Mitigation Plan will be developed to avoid or manage the PAG materials. Management techniques may include neutralizing material addition, encapsulation, or disposal in a subtitle D landfill.

In conjunction with the Mitigation Plan, a site-specific Monitoring Plan will be developed prior to construction for documenting the effectiveness of PAG rock mitigation measures and for assessing the level of potential impacts to the environment. The Monitoring Plan will include sampling and analytical procedures, analytical parameters, frequency of monitoring, and monitoring locations. At project completion, the mitigation-related features will be recorded on the geotechnical asset management (GAM) layer in MnDOT's ArcIMS (Georilla) to facilitate annual maintenance inspections and provide information on future projects.

CHAPTER 1: INTRODUCTION

This chapter introduces the purpose of the *MnDOT Guidance Manual for Potentially Acid-Generating Materials in Northern Minnesota* (PAG Guidance), provides a summary of the PAG Guidance's organization, and introduces several definitions and concepts used throughout.

1.1 PURPOSE OF THE DOCUMENT

The purpose of the PAG Guidance is to assist MnDOT with evaluating, managing, and mitigating materials that may be acid-generating during highway construction and/or maintenance projects. The geographic focus of the PAG Guidance is limited to MnDOT Districts 1 and 2 (Figures 1.1 and 1.2), which represent the areas of Minnesota where bedrock is not only near to the surface but also contains sulfide minerals (acid generating) that are generally more prevalent than carbonate minerals (neutralizing agent). Benefits associated with using the PAG Guidance include increased longevity of highways and related structures, reduced potential for environmental impacts during construction and maintenance, and overall lifecycle cost savings.

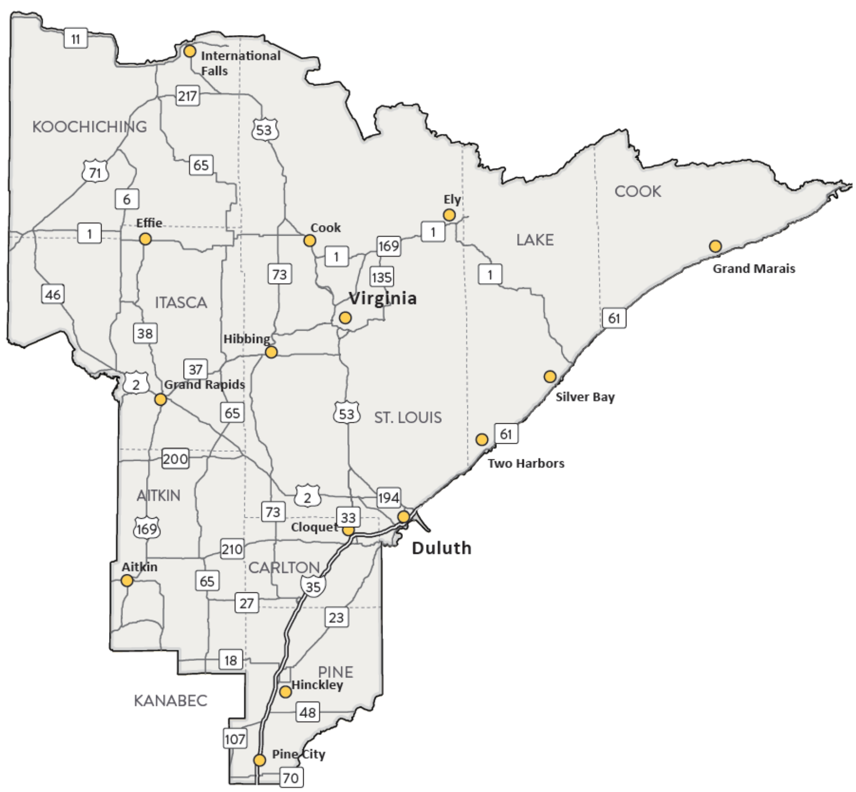


Figure source: [Minnesota Department of Transportation website]

Figure 1.1 MnDOT District 1.

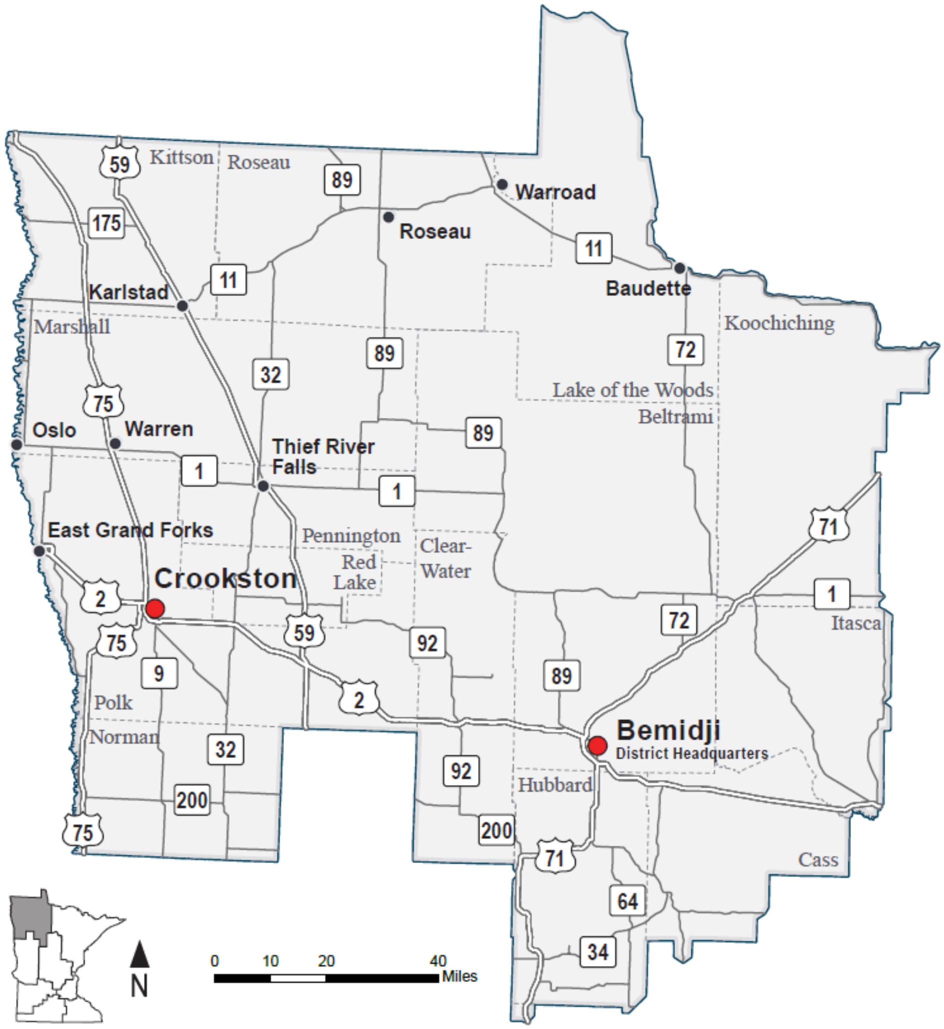


Figure source: [Minnesota Department of Transportation website]()

Figure 1.2 MnDOT District 2.

1.2 KEY CONCEPTS

Certain naturally occurring minerals, such as iron sulfides, have the potential to generate acid if exposed to oxygen and moisture. This exposure can either occur due to natural or human-influenced activities, including excavation and earthwork. When these acid-generating reactions occur, the result is a change in pH in the water contacting the mineral that can subsequently release metals and other constituents, which is called acid rock drainage (ARD). However, other naturally occurring minerals, such as carbonates and silicates, have the potential to neutralize the reaction. This PAG Guidance describes material testing, interpretation of results and mitigation practices associated with ARD in support of minimizing potential impacts to the environment associated with MnDOT projects.

1.3 ORGANIZATION

Project-specific considerations, including geologic setting, scope of the project, and proximity to sources of neutralizing materials, influence project decisions to avoid, evaluate, preemptively treat, and/or mitigate PAG materials. These considerations also influence any associated monitoring for potential impacts. Therefore, the PAG Guidance is organized as follows:

Chapter 2 provides an overview of northern Minnesota's geologic history and relevant mineral occurrence.

Chapter 3 summarizes geochemical reactions associated with PAG materials and factors that influence rates of reaction.

Chapter 4 outlines the decision-making framework for evaluating the proposed project scope to determine the need for investigating, screening, characterizing, mitigating, and monitoring activities.

Chapter 5 describes field methods for investigation, including sample collection and logging, field observations, and individual considerations for evaluating rock, overburden, and import materials.

Chapter 6 provides guidance for analytical testing methodology and interpretation of results.

Chapter 7 describes mitigation and treatment approaches for transportation projects.

Chapter 8 outlines requirements for pre- and post-construction monitoring to evaluate and document potential impacts to surrounding features associated with project implementation.

1.4 DEFINITIONS

For the purpose of this PAG Guidance, below are the definitions of the more commonly used terms:

Acid base accounting (ABA): The procedures and calculations used to test and assess the potential for a material to generate acid rock drainage.

Acid rock drainage (ARD): A chemical interaction between minerals (often sulfur-bearing minerals in Minnesota) and environmental water and/or oxygen that results in a decrease in pH in the water contacting the minerals.

de minimis: A threshold set of project conditions in which the PAG material to be disturbed is a small volume (<200 cubic yards) and has a sulfur content less than the defined threshold (<1.0%).

Geotechnical Asset Management (GAM): A digital data set in MnDOT's ArcIMS (Georilla) to facilitate annual maintenance inspections and provide information for future projects.

Metal leaching (ML): The release of metals, commonly associated with ARD due to reduced pH.

Potentially acid-generating (PAG) material: Materials that meet the definition of PAG, based on testing results (Section 6.8). The mineralogical composition of these materials are characterized as having more potential to generate acid than to neutralize acid.

Preemptive mitigation: Mitigation occurring for *de minimis* conditions, using a conservative treatment rate.

Qualified Professional (QP): Minnesota-licensed professional geologist, geological engineer, or other qualified individual who has experience identifying PAG deposits and familiarity with northern Minnesota geology.

Water Treatment Professional (WTP): Minnesota-licensed professional engineer or other qualified individual who has experience with aqueous treatment of metal leaching and other ARD-related potential discharges.

CHAPTER 2: GEOLOGY OF NORTHERN MINNESOTA

This chapter describes the geologic history of northern Minnesota, outlining the major lithologies, associated minerals, and their potential to be acid-generating and/or neutralizing. The understanding of the geology of northern Minnesota is derived from the significant volume of research and exploration conducted due to the economic potential of the bedrock in northern Minnesota as well as the abundance of Precambrian-aged exposures. For a more detailed history of northern Minnesota, see Peterson 2018 (Appendix A). A summary of literature-derived and project-specific sulfur content and associated neutralization potential (NP) for several predominant geologic units in northern Minnesota are tabulated in Section 2.3.

The project setting, including the geology and associated mineralogy described in this chapter, will inform the appropriate level of effort for investigation and, if necessary, mitigation and monitoring efforts.

2.1 GEOLOGY

The general geology of northern Minnesota consists of Neoarchean granites and greenstones of the Superior Province, overlain by younger Paleoproterozoic iron formations and deep-marine argillites (Animikie Basin) which, collectively, were intruded by the Duluth Complex and overlain by volcanics of the North Shore Volcanic Group during the Mesoproterozoic (Midcontinent Rift System). Glaciations in the Quaternary have scoured these formations, leaving a veneer of glacial drift of variable thickness. In some wetlands of northern Minnesota, post-glacial processes formed sulfides in oxygen-depleted, water-rich hydromorphic environments (in or below organic/wetland environments). The mineralogical components of the bedrock and surficial deposits include sulfur- and carbon-bearing minerals that are subject to weathering and leaching upon exposure at the surface.

2.1.1 Bedrock Geology

Sims and Morey (1972) note that the Neoarchean rocks in northern Minnesota are predominantly comprised of mafic to felsic volcanic rocks, greywacke-type sedimentary rocks, or granitic rocks. Both the volcanic and sedimentary rocks originated from processes related to island arc volcanism and subduction and have been subjected to greenschist-facies type metamorphism. Over-thickening of these “greenstone belts” enabled partial melting of the lower crust, leading to granite intrusions. Thus, the term granite-greenstone terrane is generally used to describe the Neoarchean (Sims and Morey 1972). Neoarchean geologic units may or may not contain significant sulfur, but sulfur-bearing minerals are commonly associated with the shear zones that cross cut the greenstone-granite terrane. Sulfide-bearing formations meeting this description include the Soudan Iron Formation (Algoma-type iron formation) and the Lake Vermillion Formation. Additionally, these formations also contain some carbonates and silicates that may contribute to overall potential for neutralization (J. F. Machamer 1968).

The Paleoproterozoic rocks of Minnesota are primarily characterized by the Animikie Group, which includes three Superior-type iron formation sequences: the Mesabi Range, the Gunflint Range, and the Cuyuna Range. Each formation sequence, or lithostratigraphic package, consists of a basal arenite, a Superior-type iron formation with an intermediate slate layer, and an upper greywacke slate (Morey 1972); (Ojakangas et al. 2005); (Jirsa, Miller, and Morey 2008). The iron formations themselves are comprised of alternating layers of slates and chert. The slaty layers often contain both sulfide minerals and mixed-cation carbonates (such as siderite); the highest proportion of sulfides coming from the Lower Slaty (specifically the Intermediate Slate). Other carbonates (such as limestone) are also present in the iron formations in distinct units. The overlying slates (such as the Virginia and Rove Formations) are also known to contain sulfide minerals (Morey 1972); (Ojakangas et al. 2005); (Jirsa, Miller, and Morey 2008).

Following the deposition of the Animikie Group, the Paleoproterozoic rocks were subjected to at least two tectonic events. Faulting and folding occurred as a result of the 1.85 Ga Penokean Orogeny. Later, during the formation of the Midcontinent Rift at 1.1 Ga, the emplacement of the Duluth Complex caused regional-scale thermal metamorphism [(Morey and Southwick 1995); (Schulz and Cannon 2007); (French 1968); (McSwiggen and Morey 2008); (Jirsa, Miller, and Morey 2008)]. This contact metamorphism mobilized, consolidated, and recrystallized the sulfide minerals present in the country rock (Biwabik Iron Formation). Disseminated sulfide minerals and massive sulfide occurrences can be found throughout the Duluth Complex, although they are most concentrated in areas adjacent to the country rock, such as the Virginia Formation, from which the sulfur was scavenged during emplacement.

2.1.2 Quaternary Geology

Northern Minnesota's geologic terrane was impacted by numerous advances and retreats of glaciers from the Laurentide ice sheet. These advances occurred from three directions: from the northeast through the Superior Basin (Superior Lobe), from the northeast through southern Canada (Rainy Lobe), and from the northwest toward the Superior basin (Koochiching Lobe and St. Louis sublobe; Hill, 2007). In northern Minnesota, glacial material is thickest in the northwest, with less amounts toward Lake Superior.

The composition of the glacial material present is ultimately dependent on the path of the ice lobes. For example, Superior lobe drift deposited south and southwest of Duluth during the Automba phase is a red sandy till with red sandstone and shale from the Lake Superior Basin, whereas the Highland moraine along the Lake Superior shore contains Duluth Complex. Conversely, the drift of the St. Louis sublobe north of the Itasca moraine has fragments of Cretaceous shale, whereas near Giants Range it is likely reworked glacial and glacial lake sediments (Wright Jr., 1972). Therefore, glacial drift and associated deposits throughout Minnesota contain rock from northern Minnesota and Canadian terranes and, thus, contain varying amounts of potentially acid-generating and acid-consuming minerals.

2.1.3 Hydromorphic Environments

PAG surficial materials occur in reducing hydromorphic environments that favor the *in-situ* formation of sulfide (acid sulfate soils). In Minnesota, these conditions typically occur in or below organic (wetland) environments. When these soils are exposed to atmospheric oxygen, dissolution of sulfides can occur.

2.2 MINERALOGY

Sulfur- and carbonate-bearing minerals are present in the matrix of many geologic units found in northern Minnesota and are associated with volcanic, sedimentary, and metamorphic processes. Table 2-1 summarizes the common acid-generating and acid-consuming minerals known to be present in the geologic provinces of northern Minnesota. These minerals are described further in Sections 2.1 and 2.2.

Table 2-1 Major geologic terranes of northern Minnesota

Geologic Terrane	Common Acid-Generating Minerals	Common Acid-Consuming Minerals
Mid-Continent Rift System	Primary: Pyrrhotite, chalcopyrite Lesser: Pentlandite, cubanite (+ many other minor occurrences)	Mafic silicates, calcic plagioclase
Animikie Basin sediments (including Biwabik Iron Formation)	Primary: Pyrite, pyrrhotite	Calcite, magnesium-iron carbonates, silicates
Neoarchean Granite-Greenstone terranes	Primary: Pyrite Lesser: Pyrrhotite, chalcopyrite, covellite, chalcocite	Calcite, carbonates (veins), silicates

2.2.1 Sulfur-Bearing Minerals

The predominant sulfide-bearing minerals in northern Minnesota are pyrite (FeS_2) and pyrrhotite ($Fe_{(1-x)}S$, where x ranges between approximately 0 to 0.2). Lesser occurrences of other sulfides include, but are not limited to, marcasite (FeS_2), chalcopyrite ($CuFeS_2$), pentlandite [$(Fe,Ni)_9S_8$], sphalerite [(Zn,Fe)S], bornite (Cu_5FeS_4), tetrahedrite [$(Cu,Fe)_{12}Sb_4S_{13}$], arsenopyrite (FeAsS), galena (PbS), talnakhite [$Cu_9(Fe,Ni)_8S_{16}$], chalcocite (Cu_2S), and cobaltite (CoAsS). Additionally, sulfate minerals, such as gypsum ($CaSO_4 \cdot 2H_2O$), jarosite [$KFe_3(OH)_6(SO_4)_2$], and melanterite ($FeSO_4 \cdot 7H_2O$), may also be present, especially in mine wastes and other rocks that have been subject to weathering. Many (but not all) of these sulfur-bearing minerals have the potential to contribute to the acid-generating capability of a given geologic unit. As discussed in subsequent sections of this PAG Guidance, the quantifiable ability of a material to create acid is referred to as acid-generating potential (AP).

2.2.2 Acid-Consuming Minerals

The NP of a given material is a measure of the amount of acidity that can be consumed by the material. The rate at which the acidity is consumed, and the total amount of acidity that may be consumed varies based on the minerals present. NP is most readily associated with calcium and magnesium carbonate minerals found in limestone and dolomite. In northern Minnesota, the most common rocks with significant NP are the magnesium-iron carbonate forms found mostly within the Lake Superior-type iron formations (specifically, the Biwabik Iron Formation). It is important to differentiate Lake Superior-type iron formations from the older, Algoma-type banded iron formations (e.g., the Soudan Iron Formation). While the former contain abundant carbonates, the older banded iron formations typically contain little to no carbonate. Lesser amounts of calcium and magnesium carbonates are found in northern Minnesota, often in veins. When measured NP is attributed to geologic units lacking calcium and magnesium carbonates, additional considerations may be warranted as rates of acid neutralization may be significantly lower. Further, some minerals, such as graphite, silicates, and iron or manganese carbonates (siderite and rhodochrosite) may yield confounding NP results due to more complex geochemical reactions. A discussion on these minerals as well as silicate dissolution rates is included in Section 6.1.

2.3 CASE STUDIES

Due to the general lack of significant inherent neutralization capability in the rocks of northern Minnesota, reactivity and the potential for ARD generation are often primarily a function of sulfur content. Investigations into rock management for mines in northern Minnesota has resulted in a handful of publicly available measurements of sulfur and NP for formations that may be encountered by MnDOT during projects involving rock excavations. The results from a selection of these studies are summarized in Tables 2.2 and 2.3. The highest sulfur percentages have typically been associated with the Soudan Iron Formation (an example of an Algoma-type iron formation) and the Virginia Formation (the extensive Paleoproterozoic metasediments overlying the Biwabik Iron Formation). The highest NP values have typically been associated with the relatively extensive carbonates found within the Biwabik Iron Formation.

Table 2.2. Sulfur characteristics of northern Minnesota rocks, based on the results of ABA investigations

Lithology	Sample Count	Sulfur Range (weight %)	Notes/Investigation
Soudan Iron Formation	383	<0.01 - 10.6	Eagles Nest (Heine et al., 2017)
Soudan Volcanoclastics and Basalts	99	<0.01 - 0.64	Eagles Nest (Heine et al., 2017)
Lower Ely Basalts	26	<0.01 - 0.04	Eagles Nest (Heine et al., 2017)
Dacite Porphyry Intrusion	335	<0.01 - 0.87	Eagles Nest (Heine et al., 2017)
Virginia Formation	25	0.06 – 5.68	As sulfide; Mesabi Nugget (HCItasca, 2010); Northmet (Barr, 2014); Northshore (Golder, 2012)
Biwabik Iron Formation – Upper Slaty (A)	1	0.3 - 0.3	As sulfide; Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation – Lower Slaty (P)	8	0.02 - 0.33	As sulfide; Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation – Lower Slaty (Q)	4	2.48 - 2.84	As sulfide; Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation – Lower Cherty (R)	6	0.02 - 0.33	As sulfide; Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation	80	0.001 - 1.55	UTAC (United Taconite, 2018)
Duluth Complex	85	0.02 - 4.46	Northmet (Barr, 2014)
Duluth Complex – Troctolite	12	0.007 - 0.032	MnDOT TH1 Kawishiwi (personal communication MnDOT, 2019)

Table 2.3. NP characteristics of northern MN rocks, based on the results of ABA investigations

Lithology	Sample Count	NP Range (kg $CaCO_3$/metric ton rock)	Notes/Investigation
Soudan Iron Formation	383	2 - 191	Eagles Nest (Heine et al., 2017)
Soudan Volcanoclastics and Basalts	99	6 - 155	Eagles Nest (Heine et al., 2017)
Lower Ely Basalts	26	16 - 97	Eagles Nest (Heine et al., 2017)
Dacite Porphyry Intrusion	335	2 - 185	Eagles Nest (Heine et al., 2017)
Virginia Formation	21	4.2 - 42.4	Mesabi Nugget (HCItasca, 2010); Northshore (Golder, 2012)
Biwabik Iron Formation – Upper Slaty (A)	1	656	Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation – Lower Slaty (P)	8	24 - 94	Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation – Lower Slaty (Q)	4	44 - 77	Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation – Lower Cherty (R)	6	18 - 78	Mesabi Nugget (HCItasca, 2010)
Biwabik Iron Formation	80	3.92 - 462.1	UTAC (United Taconite, 2018)
Duluth Complex – Troctolite	12	2.3 - 4.7	MnDOT TH1 Kawishiwi (Personal communication MnDOT, 2019)

CHAPTER 3: UNDERSTANDING ACID ROCK DRAINAGE

This chapter presents an overview of the processes that control the production and neutralization of acidic geologic materials. General geochemical reactions and descriptions of some of the more pertinent factors that influence ARD are included. A substantial set of literature exists on the topic of ARD, and many detailed review documents are publicly available (e.g., INAP 2014, MEND 2009). Characterization of the potential for acid generation and mitigation before and during construction will inform the approaches to avoid negative outcomes associated with disturbance of PAG materials.

As discussed in Chapter 2, the primary minerals responsible for PAG material in Minnesota are iron sulfides. PAG material is a concern in transportation projects that involve alterations to geologic features (e.g., road cuts), which, if not mitigated, could result in ARD. ARD is the process in which the chemical interaction between sulfur-bearing minerals and environmental water and/or oxygen results in a decrease in pH in water contacting the minerals. During construction, the fresh exposure of sulfide minerals to moisture and oxygen can result in ARD and an accompanying release and mobilization of potentially toxic metals and other elements. The products of ARD can lead to negative effects on infrastructure, ecosystems, and the environment.

ARD can be neutralized in the environment by natural and/or intentional human activities. When ARD mobilizes metals or other elements, subsequent neutralization may affect the pH of the water, but the metals may remain dissolved. Under some conditions, the metals and other elements may precipitate when the pH increases. The release of metals is referred to as metal leaching (ML). Commonly, the ARD and ML reactions are jointly referred to as ARD/ML. The focus of this PAG Guidance is ARD evaluation and mitigation. If ML conditions are observed through the monitoring activities described in Chapter 8, additional consideration (i.e., water treatment) outside the scope of this PAG Guidance may be merited.

In addition, crushing PAG material, such as for use as fill during construction, can result in increased sulfide mineral exposure, leading to further ARD potential as particle size is reduced and material is spread further (Hammarstrom, Brady, and Cravotta 2005; Hindar and Nordstrom 2015). The general negative effects of ARD include corrosion (Bryant 2003; Orndorff and Daniels 2002), ground destabilization (Bryant 2003; Orndorff and Daniels 2002), toxicity to vegetation and aquatic organisms (Morin et al. 2003; Hindar and Nordstrom 2015), and water quality degradation (Hammarstrom, Brady, and Cravotta 2005; Viadero and Fortney 2015).

3.1 ARD GEOCHEMISTRY

The primary minerals in PAG material in Minnesota are the iron sulfides pyrite and pyrrhotite. Chapter 2 of this document discusses the geologic provenance of these minerals in northern Minnesota. As stated above, when exposed to moisture and oxygen, iron sulfides can oxidize to produce sulfuric acid (H_2SO_4, or $2H^+ + SO_4^{2-}$) according to the following equations:

$$FeS_2(s) + \frac{7}{2}H_2O + \frac{15}{4}O_2 = Fe(OH)_3(s) + 4H^+ + 2SO_4^{2-}$$ **Equation 1**

$$Fe_{(1-x)}S(s) + \frac{5\text{-}3x}{2}H_2O + \frac{9\text{-}3x}{4}O_2 = (1\text{-}x)Fe(OH)_3(s) + 2H^+ + SO_4^{2-}$$ **Equation 2**

Some sulfide minerals, such as covellite (CuS, used in the examples below), sphalerite, and galena, do not produce acid when oxidized by oxygen:

$$CuS(s) + 2O_2 = Cu^{2+} + SO_4^{2-}$$ **Equation 3**

However, the weathering of iron-bearing phases can result in dissolved ferric iron, which may act as an oxidant for sulfide-bearing minerals under acidic conditions (pH less than approximately 4), including minerals that do not generate acid through oxidation by oxygen:

$$CuS(s) + 8Fe^{3+} + 4H_2O = Cu^{2+} + 8Fe^{2+}\ SO_4^{2-} + 8H^+$$ **Equation 4**

These oxidation processes can be catalyzed by microbial activity; the presence of certain microbial species can accelerate or continue acid production from sulfide minerals under conditions where these reactions would be less thermodynamically favorable. For example, bacteria can oxidize ferrous iron to ferric iron in low-oxygen conditions where the process may not occur abiotically.

3.2 MINERAL AVAILABILITY

The quality and quantity of mineral surfaces exposed affect the availability of the mineral for reaction. Therefore, a mineral's "availability" may also be considered in the evaluation of a material's potential to produce ARD (Price and Errington 1998). Particle size distribution and armoring or encapsulation of the mineral grains are two primary factors controlling this availability. Because the specific surface area (surface area per unit mass) of a mineral particle increases exponentially as particle size decreases, the total reactivity is a function of both the abundance of particular minerals and their respective particle sizes, with the most reactive fraction generally being the less than 0.078 inches (2 mm) size fraction (Price and Errington 1998; International Network for Acid Prevention 2014). In rock fragments that contain numerous mineral grains, the area of a particular mineral grain that is exposed can control its reactivity. Mineral coatings (such as sulfates or iron oxides on iron sulfide minerals) may limit minerals from participating in acid generation or neutralization reactions. For example, an iron oxide coating on the surface of an iron sulfide mineral particle can decrease the availability of oxygen for oxidation reactions. The development of these coatings over time can inhibit ARD in natural settings, but earthmoving activities, such as mining and construction, can rapidly create available fresh (unweathered) mineral surfaces.

CHAPTER 4: PROJECT SCREENING AND ASSESSMENT

This chapter describes the overall approach for screening and assessment of PAG materials (rock and unconsolidated) associated with projects encountering or excavating rock in MnDOT Districts 1 and 2. The MnDOT Geology Unit has tools and experience to aid the project, and the capability to engage with and manage external qualified professionals (QPs). The process described for determining whether a project needs to be referred to the MnDOT Geology Unit is illustrated in Figure 4.1. Preferably, the decision to refer a project to the MnDOT Geology Unit should be made during the project scoping process.

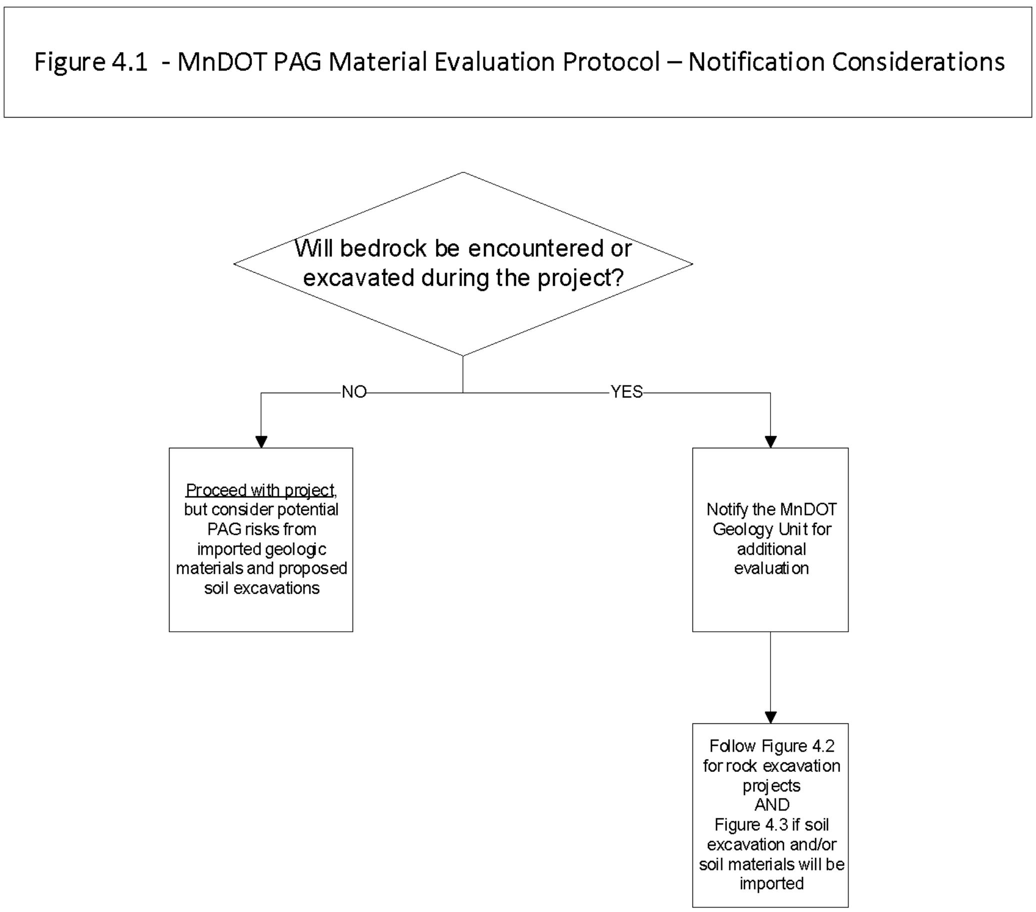
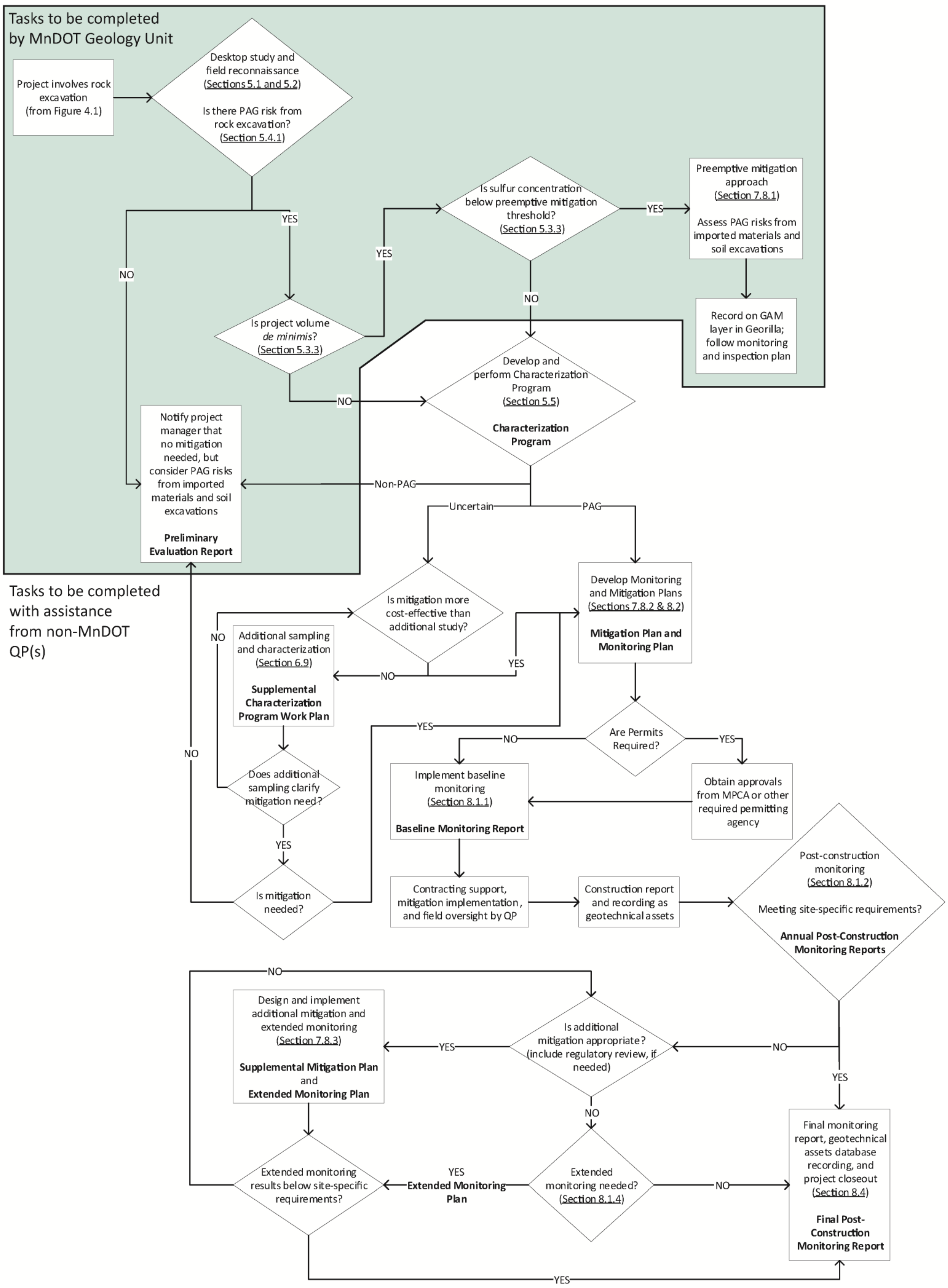


Figure 4.1 MnDOT PAG material evaluation protocol – notification considerations.

If the potential for encountering bedrock or performing rock excavation is likely, the MnDOT Geology Unit should be notified by the project manager to begin PAG rock-related evaluations and, potentially, soil excavation and import related investigations.

If the potential for encountering bedrock or performing rock excavation is unlikely, project managers may proceed with the project but are encouraged to consider PAG-related risks associated with soil excavations as well as with importing geologic materials (bedrock or unconsolidated).

Processes for evaluation of projects encountering or excavating rock are summarized on Figure 4.2, while processes for evaluation of unconsolidated materials are summarized on Figure 4.3.



Notes:
References to text sections are <u>underlined</u>

Project documentation and deliverables are in **bold**

BARR

Figure 4.2

Rock Excavation Project
PAG Evaluation Process

MnDOT Guidance Manual for
Potentially Acid Generating Materials
in Northern Minnesota

Figure 4.2 Rock excavation project.

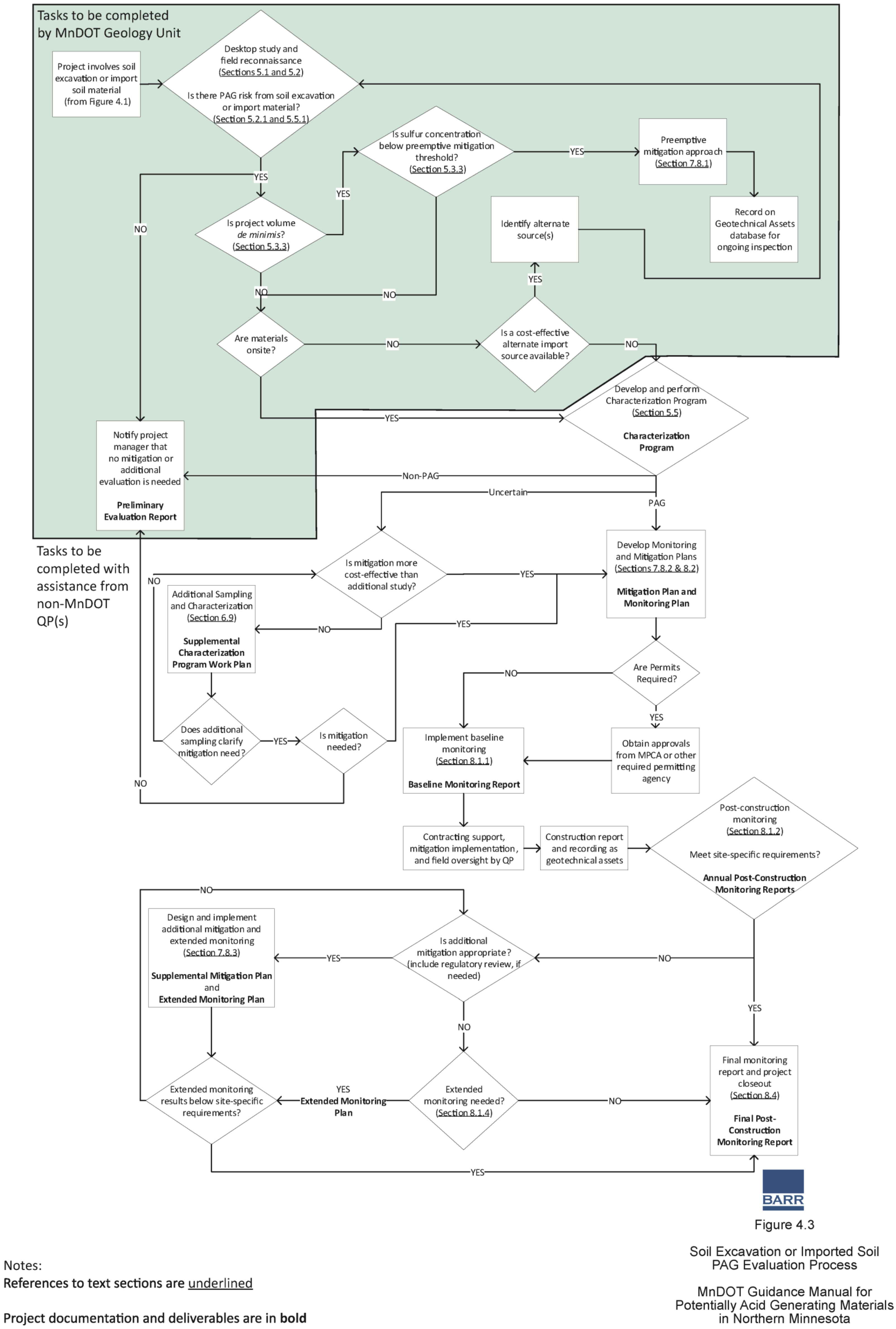


Figure 4.3 Soil excavation or imported soil.

4.1 PROJECT EVALUATION PROCESS OVERVIEW

The MnDOT Geology Unit will evaluate the proposed project scope and will perform a preliminary evaluation for the presence or absence of PAG materials. If necessary, a Characterization Program (CP) will be developed. If needed based on the characterization results, a Mitigation Design (MD) Plan and a Monitoring Plan will be created. In general, the steps include:

- Desktop study and field reconnaissance (Sections 5.1 and 5.2);
- Preliminary evaluation and *de minimis* determination (Section 5.3);
- Characterization Program development and implementation (Section 5.4);
- Laboratory testing and analysis (Chapter 6);
- Data interpretation (Section 6.8);
- Mitigation planning and design (Chapter 7);
- Baseline water quality monitoring (Chapter 8.1.1);
- Mitigation implementation, including testing during construction (Chapter 7); and
- Post-construction monitoring (Chapter 8).

All projects involving rock excavation will initially be subjected to a desktop study and field reconnaissance to determine the potential presence of PAG material. Results of those activities may indicate that no further evaluation is necessary, that preemptive mitigation approaches may be applied, or that a Characterization Program should be developed and implemented.

For projects that include PAG evaluation of imported materials or soil excavation, a desktop study will be performed. If PAG materials are identified as part of a potential import source, options exist for either further evaluation of the proposed import material, or for consideration of an alternate import source. Depending on the volume of material needed and the proximity of the alternate import source, the mitigation of import materials may occasionally be more cost-effective than the increased trucking costs associated with using another import source.

4.2 CHARACTERIZATION PROGRAM

A Characterization Program will be developed if results from the desktop study and field reconnaissance suggest that more extensive site evaluation is necessary. The Characterization Program will outline the methods and rationale for acquiring representative surface and subsurface samples of rock and soil, as needed, and the analytical procedures. Chapter 5 describes sampling methods, strategies, and minimum sampling requirements. Laboratory analytical tests and calculations used to evaluate the materials for acid generation and associated risk are described in Chapter 6. The results of the analytical testing will categorize the materials into one of three categories: non-PAG, uncertain, or PAG. The specific determination criteria for each category are included in Section 6.8.

Projects with PAG materials planned for disturbance will require mitigation and monitoring, as described in Chapters 7 and 8, respectively.

If the materials are determined to be non-PAG, the project will not require mitigation or monitoring for ARD-related concerns. The project manager will be provided a summary memo documenting the project evaluation and results for project recordkeeping.

If the materials do not meet the designation of PAG or non-PAG, they are deemed “uncertain”. Uncertain material classification will require additional steps to further refine the classification, or, if more cost-effective than additional study, uncertain material may be assumed to be PAG material. If additional study is appropriate, a Supplemental Characterization Plan will be developed and implemented. The results of the Supplemental Characterization Plan will be reiterated until a determination of PAG or non-PAG is reached, or that mitigation is deemed more cost-effective than further study.

4.3 MITIGATION AND TREATMENT DESIGN

Results from the Characterization Program will dictate the mitigation approach and scale prior to project execution, as described in Chapter 7. Design of PAG material repositories may follow the general descriptions offered in Chapter 7, but will need to be developed by a QP. Site-specific conditions related to hydrogeology, background water quality, road layout, slopes, erosion, storm water management, and utilities will need to be incorporated into a holistic design approach, as reported in the Mitigation Design and Monitoring Plan. Mitigation objectives for ARD and treatment objectives for effluents, discharges or ML will be based on the baseline water quality, the volume and chemistry of the PAG materials, and site-specific considerations.

In some cases, the potential for using or disturbing PAG material will affect considerations for project permitting. Conditions or requirements relating to the protection of water resources are common in individual construction permits such as storm water management and wetland permits. Early coordination with permitting authorities is advantageous because data collected during investigation can be used as the basis for permit conditions, if necessary.

4.4 BASELINE MONITORING

In situations where mitigation and monitoring will be required, baseline monitoring will also be required prior to construction activities to provide context for pre-disturbance conditions. Baseline monitoring may also be a component of permits associated with the construction activities. Recommendations for monitored media, methods, frequencies, parameters, and reporting are provided in Chapter 8.

4.5 IMPLEMENTATION OF MITIGATION/TREATMENT

During road construction and concurrent mitigation implementation, a QP shall be present to provide documentation of design adherence and technical assistance. Guidance for specific construction-related screening, sampling, and observations will be provided on a project-specific basis, in the Mitigation Design and Monitoring Plan for the project (Chapters 7 and 8).

4.6 POST-CONSTRUCTION MONITORING

Post-construction monitoring will be performed to evaluate the effectiveness of the mitigation. This data will be documented and compared to pre-construction conditions to assess performance of applied mitigation approach and potential need for further mitigation options. Recommendations for monitored media, methods, frequencies, parameters, and reporting are provided in Chapter 8.

If post-construction monitoring results do not meet site-specific goals during or following the post-construction monitoring period, the project will either need supplemental evaluation, an extended monitoring period (Chapter 8), or treatment of affected media (Chapter 7).

CHAPTER 5: INVESTIGATION AND SAMPLING

This chapter describes the steps to be taken to investigate and collect samples, if needed, for projects that are determined to have the potential to intersect bedrock or are located within PAG areas. Steps for soil excavations and imported material evaluations are also provided. Specific flow chart components include the desktop evaluation, field reconnaissance, and development of a Characterization Program (Figures 4.2 and 4.3).

The initial phase of investigation and sampling will include a desktop study and field reconnaissance consisting of a site visit and outcrop sampling and analysis. Based on results of the desktop study and field reconnaissance, a more thorough Characterization Program may be performed. The Characterization Program may include geophysical surveys, diamond core drilling, overburden and import source sampling, surface and groundwater sampling, and quarry sampling. Methods to select, prepare, and preserve materials are also described. The qualifications and experience of third-party contractors to meet ARD-specific sampling and analysis needs such as laboratory services, drilling, and other technical specialties should be evaluated. Specialized engineering sections within MnDOT should also be considered for field reconnaissance and components of the Characterization Program, including surveying, sample collection, geophysics, drilling, soil/rock logging and chemical analyses.

5.1 DESKTOP STUDY

The desktop study will use readily available resources describing the site geology and hydrology in which the project is proposed to determine whether there is PAG risk from bedrock sources; it may also be used to assess proposed soil excavations and imported material sources.

The desktop study will be initiated by the project manager who will utilize the depth to bedrock map in Georilla (an internal web-map application supported by MnDOT's Asset Management Project Office) to assess the potential of encountering bedrock within their project area.

Other resources that will be used by the MnDOT Geology Unit for evaluating the project setting include the PAG ArcMap layers, as described in Appendix A (NRRI, 2018), the Steel Pipe Service Life study (Heitkamp and Marr, 2015), previously-developed information regarding site settings, and available publications related to geology, mineralogy, and potential for acid generation.

As stated in Chapter 4, if the potential for encountering bedrock or performing rock excavation is likely (based on depth to bedrock assessments by the project manager), then the MnDOT Geology Unit should be notified. The MnDOT Geology Unit will verify the findings using the resources described above. If it is determined that bedrock will be encountered or excavated during the project, the MnDOT Geology Unit will proceed to Field Reconnaissance (Section 5.2).

If a project manager determines that it is unlikely that bedrock will be encountered or excavated during a project then it may proceed without further study, but an assessment of potential PAG risks from imported materials and proposed soil excavations should be considered but performed by a QP.

For imported crushed bedrock sources, field reconnaissance may be performed beginning with a site visit (see section 5.2.1). For imported or excavated soils, the Steel Pipe Service Life study (Heitkamp and Marr, 2015) may be consulted as a screening tool for identifying PAG soils in a project area by the MnDOT Geology Unit. The development of the Steel Pipe Service Life study characterized the pH and resistivity of soils within transportation corridors statewide. Northeast Minnesota generally had the lowest soil pH, and highest soil resistivity values, and the majority of acidic soils were located less than 10 miles from wetlands. Given this strong relationship to saturation, wetland and hydrologic coverages should be considered during the desktop study to evaluate whether saturated and chemically-reduced soils may be encountered as part of the project. If a desktop study is performed and suggests that imported or excavated soils may be PAG, a site visit should be performed and soil sampling and testing should be performed during the geotechnical subsurface investigation program (see Section 5.4.1).

5.2 FIELD RECONNAISSANCE

A preliminary field assessment or initial site reconnaissance of the excavation areas should be completed by the MnDOT Geology Unit or other qualified personnel (QP). Field reconnaissance will involve all or some of the following: description of field observations, collection of hand samples, and field and lab testing. A site visit and outcrop sampling and analysis will be performed for all proposed rock excavations greater than 200 cy.

5.2.1 Site Visit

Site visits will involve walking the entire site and examining water, vegetation, and rock features for signs of PAG material or ARD. These signs include:

- **Oxide staining in streams**, observed as orange-red streambed sediments;
- **Stressed or unhealthy vegetation**. Although not diagnostic, low pH environments impact nutrient uptake and disease resistance of many plant species, resulting in effects such as wilting, yellowing of leaves (chlorosis), leaf bronzing or stippling;
- **Iron staining and/or efflorescence** (white encrustations or sulfate salts) on exposed rock surfaces;
- **Visible pyrite, pyrrhotite, or other sulfide minerals** on exposed rock surfaces, especially those that may be disturbed during construction;
- **Evidence of past or current surface or underground metal mining activities**.

The presence, locations, and hydrologic regimes of sensitive areas and water features, such as wells, springs, seeps, lakes, streams, and wetlands, will be mapped during the initial reconnaissance of the project. This will aid in determining the potential risk factors of the project as well as identify locations for baseline and post-construction monitoring.

The site visit also includes collecting spatial information about bedrock outcrops, if present. The location and extent of outcrops will be collected using a GPS capable of accuracy within three feet; major lithologies visible in outcrop will be noted. Visual examination, identification, and qualitative estimates of sulfide and carbonate minerals present, along with their mode of occurrences, should be made. The use of dilute hydrochloric acid should be used to confirm the presence of calcite or dolomite. The structural position of strata may be inferred from observations of strike and dip measurements of outcrops.

5.2.1.1 Imported Materials and Soil Excavations

PAG risks from soil planned for excavation and for imported material (such as sand and gravel or crushed rock sources) may be considered via site visits:

- If a site visit is performed and imported soil materials or excavated soils are suspected to be PAG, soil sampling and testing during the Characterization Program or the geotechnical/pre-design subsurface investigation program should be performed (Section 5.4.1). *De minimis* conditions and preemptive mitigation measures may be considered as described in 5.3.3.
- For crushed bedrock sources, if signs of PAG material or ARD are observed during the site visit, outcrop sampling and analysis should be performed.

If no signs of PAG material or ARD are observed during the site visit, no further action is required.

5.2.2 Outcrop Sampling and Analysis

Outcrop sampling and analysis will be performed on representative rock that will be intersected by the project for all rock excavations greater than 200 cy (unless the formation is historically devoid of sulfide and verified by site visit), or if the likely presence of PAG material or ARD is observed during the site visit. In those instances, at least one representative sample per lithology present in outcrop will be collected. The location of hand sample collection will be recorded, and the hand samples will be labeled with the location and date of collection (see Appendix B for technical references and guidance, including a sample outcrop description sheet).

Drilling may be substituted for outcrop sampling (if preferred over outcrop sampling) but is necessary if bedrock outcrops are not present in the project area, and may also be used to augment outcrop sampling. Drilling may be performed in a fashion which satisfies geotechnical/subsurface information needs. Sample size and selection may follow guidance in section 5.4.2.1.

For bedrock, outcrop samples will be assessed by analyzing total sulfur and carbon content via combustion-infrared spectrophotometer. If necessary, soil excavation areas and imported unconsolidated materials will be screened via paste pH and paste electrical conductivity (see Figure 4.2). Sample preparation, analysis, and PAG risk thresholds are addressed in Section 6.4.

5.3 INITIAL PAG DETERMINATION

The results of the desktop study and field reconnaissance will determine the need for a Characterization Program. Findings will be documented and submitted to the project manager. The following statements provide decision guidance for both bedrock excavations and imported crushed bedrock sources and provide clarity to the decision-making processes outlined in Figures 4.2 and 4.3.

5.3.1 Bedrock Excavations

If the results of the desktop study and field reconnaissance suggests that:

- PAG bedrock is not present, then no further evaluation, monitoring, or inspection will be required. However, PAG risks from imported materials and soil excavations should be considered and performed by a QP.
- PAG bedrock is present AND greater than 200 cy of rock excavation is proposed, then the study will proceed to a Characterization Program (Section 5.4).
- PAG bedrock is present AND less than 200 cy of rock excavation is proposed AND sulfur concentrations are below the established threshold (1.0 weight percent [wt %]), then, per the *de minimis* criteria (Section 5.3.3), preemptive mitigation measures may be applied (Section 7.8.1) and therefore no Characterization Program is necessary. The treated material will be recorded on MnDOT's Geotechnical Asset Management layer in Georilla. These small project volumes will not trigger the need for groundwater or surface water monitoring. PAG risks from imported materials and soil excavations should be assessed using methods described in the Characterization Program (Section 5.4).
- PAG bedrock is present AND less than 200 cy of rock excavation is proposed BUT sulfur concentrations exceed the established threshold (1.0%), then the study will proceed to a Characterization Program (Section 5.4).

5.3.2 Imported Crushed Bedrock

If crushed bedrock sources were evaluated, the results of the desktop study, field reconnaissance, and outcrop sampling and analysis (if conducted) on imported crushed bedrock suggests that:

- PAG material is not present, then no further evaluation, monitoring, or inspection will be required.
- PAG material is present at a source volume greater than 250 cy of crushed bedrock (loose volume), the study will proceed to a Characterization Program (Section 5.4) or an alternate source will be considered.
- PAG material is present at a source volume less than 250 cy of crushed bedrock (loose volume), AND the sulfur concentrations are below the established threshold (1.0 wt %), then, per the *de minimis* criteria (Section 5.3.3), preemptive mitigation measures may be applied (Section 7.8.1) and therefore no Characterization Program is necessary. The treated material will be recorded

on MnDOT's Geotechnical Asset Management layer in Georilla. These small project volumes will not trigger the need for groundwater or surface water monitoring.

- PAG material is present at a source volume less than 250 cy of crushed bedrock (loose volume) is proposed AND sulfur concentrations exceed the established threshold (1.0 wt %), then the study will proceed to a Characterization Program (Section 5.4) or an alternate source will be considered.

5.3.3 *De minimis* Considerations

The total project volume of excavated bedrock (i.e., the sum of individual excavation volumes) will be considered in evaluating whether the project qualifies as a *de minimis* project. If the volume of bedrock to be disturbed is greater than 200 cy (bank volume) or if the average total sulfur concentration is greater than 1.0 wt. %, a Characterization Program must be developed. For projects where less than 200 cy of bedrock excavation are anticipated and average total sulfur concentrations are less than 1.0 wt %, the development of a Characterization Program will not be required. The development of the total sulfur concentration threshold is the result of a calculation of a neutralization dosing rate of 10:1, a CCE of 0.9%, and a safety factor (SF) of 2, as well as application of professional judgement for small data sets. Appendix C includes the supporting calculations. Based on the geology and generally low-sulfur-containing mineralogy in the near-surface of northern Minnesota, and the limited volume in a *de minimis* condition, the preemptive mitigation (Section 7.8.2) approach is conservative and appropriate for transportation projects. This approach may also be applied to soil excavations or imported soil materials based on analyses performed during the Characterization Program or geotechnical/pre-design subsurface investigation program.

5.4 CHARACTERIZATION PROGRAM

A Characterization Program will be performed based on interpretations from the field reconnaissance. The Characterization Program will ultimately provide a more accurate determination of the acid-generating and neutralization potential of the soil and rock to be excavated and, thus, determine the scale of PAG material mitigation. Proper site characterization will reduce environmental and public safety risks as well as project and life-cycle costs.

The Characterization Program will be developed using assistance from non-MnDOT QP(s) (as illustrated in Figure 4.2). The locations, depths, type of sampling and test methods will consider site geology as well as the project design, particularly the volume of anticipated rock and overburden excavation and imported materials. Interpretations of data and mitigation calculations will be performed by non-MnDOT QP(s).

All imported soil materials and proposed soil excavations within the project area will be assessed as part of the Characterization Program. Imported crushed bedrock sources will also be assessed if deemed necessary during field reconnaissance.

The site-specific Characterization Program will include:

- A summary of results from the desktop study and field reconnaissance activities
- Proposed sampling methods and locations (including geophysics)
- Sample quantity and selection criteria
- Testing methods
- Quality control methods

The Characterization Program should consider the data collection efforts of the geotechnical or other investigations to streamline data collection and minimize project costs.

A discussion of sample collection methods, testing methodology, and frequency are presented below.

5.4.1 Unconsolidated Surficial Materials

Imported unconsolidated materials and proposed soil excavations within the project area will be chemically analyzed during the Characterization Program or geotechnical/pre-design subsurface investigation, if the desktop study and/or site visit indicate a need. Unconsolidated surficial materials, often referred to as “overburden,” may be disturbed or removed if soil-related excavations are planned (as defined under 2105 of MnDOT Standards and Specifications for Construction). In addition, unconsolidated surficial materials may be imported to or “borrowed” from the project site or other locations for use as fill, grading, or paving material. As discussed in Chapter 2, unconsolidated surficial materials may be acid-generating, especially if deposits are adjacent to a PAG bedrock source or if they are excavated from chemically reducing environments below organic (wetland) environments or the water table (Kearney and Wenigmann, n.d.). Chemically reduced unconsolidated surficial deposits in northeastern Minnesota have the potential to contain acid-bearing sulfide minerals. Once excavated as overburden, these materials have the potential to oxidize and release sulfate and other trace metals. Well oxidized and unsaturated materials do not have this same potential for PAG risk. For this reason, an avoidance strategy which limits on-project and off-project soil excavations to above the water table will help minimize risk of chemically reduced materials being introduced on projects. For imported soil materials, other sources may be considered if PAG soils are suspected.

5.4.1.1 On-Project Surficial Materials

On-project (or *in-situ*) surficial materials should be sampled where soil excavation or disturbance is planned. Field analyses and observations will focus on the fine-grained fraction of the material gradation (fine-sand, silt, and finer-grained particle sizes). Samples may be collected via test pits or drilling methods (auger, Geoprobe, SPT, Shelby Tube). Drilling samples may be acquired in conjunction with MnDOT District auger crew drilling or during geotechnical subsurface investigations. Sample sites should be located every 500 ft on stationing along proposed centerline. Sample sites may also be located at offset locations or at each change in observed surface soil or drainage condition, as deemed necessary by QP. Section 5.2 of MPCA’s Sampling Guidance (1998) should be considered if digging test pits for sampling. Samples should be collected from 3-ft vertical increments starting from one foot below surface to 5 ft below the proposed grading depth or to bedrock, whichever is encountered first. Samples should be obtained more frequently if vertical changes in lithology, saturation, and degree of oxidation are observed. Particular attention should be paid to water table elevation and potential redox horizons; soil samples from above and below the water table should be separated to evaluate groundwater effects on soil conditions. Record the surface location of each sample site using GPS with sub-meter accuracy, record depth of samples, collect digital photographs of the sample locations and samples, and record general field conditions in a field notebook.

5.4.1.2 Off-Project Surficial Materials

Unconsolidated surficial materials imported from off-project sources for fill, base, shouldering, or similar purposes should be evaluated for potential to generate acid prior to delivery. Off-project sources may include local borrow sources or aggregate sources (sand/gravel). Since crushing of imported, unconsolidated materials is discouraged (Section 7.6.5.2), field analyses and observations will focus on the fine-grained fraction (<0.8 in or <2 mm) of the material gradation. The analyses, tests, sample acquisition methods, frequency, and additional considerations, as described in 5.5.1.1 and at the discretion of the QP, will be used to assess usage and potential for acid generation; sampling may also be performed on exposed banks within existing aggregate sources (Section 7.6.5.3). As noted above, it would be best to limit import materials to only those found above the water table, therefore, can help ensure that chemically reduced materials are not introduced on projects.

5.4.1.3 Field Observations and Testing

Field characterization will include describing the surficial materials, collection and testing of field samples and identifying the depth to groundwater (if possible). As necessary, soil excavation areas and imported unconsolidated materials will be screened via paste pH and paste electrical conductivity. To ascertain whether these chemically reduced materials are present at a project, an inspection of potential import soil areas and of the project area excavations through unconsolidated surficial materials should be conducted. Hand auger borings or auger drilling can be advanced to provide descriptions of the surficial materials that will be encountered.

Investigation of the sulfur content and leaching behavior of the chemically reduced and sulfur-bearing surficial materials may become appropriate to reduce project risks, based on the site setting and material characteristics. Useful methods for characterization are described in this section. Field evaluations and sampling should be performed by a QP. Construction stage evaluation of unconsolidated surficial materials should also be considered and is addressed in Section 7.6.5.3.

The following soil description and observations should be recorded for all overburden samples:

- Percentage of organic matter, if present;
- Relative moisture content;

- Description of oxidation features, including color of matrix and mottles, percent mottling (Munsell® and Schoeneberger et al. 2012);
- Angularity of sands and gravels (to aid in differentiating outwash from diamicton, etc.);
- Estimate percentage of lithic materials in coarse clasts; and
- Identification of visible sulfide mineralogy in matrix materials or in coarse clasts, if surfaces are not oxidized.

Perform the following field analyses, as described in Chapter 6, on each soil sample collected and record in field notebook:

- Semi-quantitative rating of reaction of 10% hydrochloric acid with matrix, and selected coarse clasts; note fizz intensity, color, and odor.
- Field rinse test for soluble salts. The procedure involves agitation of a 1:1 ratio of the matrix material and distilled or DI water to form a slurry; record the resulting "paste" pH and specific conductivity of the supernatant. A description of this test is provided in Section 6.4.2. In general, the following guidelines can be applied to interpret the results:
    - Circum-neutral to slightly basic soil paste pH is typical of oxidized northern Minnesota evergreen forest soils; pH can be as low as 2-4 in samples where readily acid-generating materials are present.
    - Low paste specific conductivity values indicate negligible amounts of any kind of readily soluble sulfides or other salts. For reference, rainwater can have specific conductivity values as high as 100 µs/cm, natural surface and groundwater are rarely as low as 50 µs/cm, and seawater is on the order of 50,000 µs/cm.
    - Redox potentials of the supernatant liquid will likely be negative in reduced soil environments. Positive redox measurements indicate that the soils are oxidized.

Signs of chemically reduced surficial materials include gleying or mottling in the zone of soil formation and rotten egg odor after reaction with dilute HCl. Samples which indicate signs of chemical reduction, or having paste values suggesting chemical reduction, should be submitted for total sulfur and carbon content via combustion-infrared spectrophotometer (see Chapter 6)

5.4.2 Subsurface Bedrock

Subsurface bedrock sampling is a critical component of the Mitigation Design development process where rock excavations are planned in PAG bedrock. Information acquired for analysis of bedrock can be collected using most types of drilling methods (i.e., diamond core drilling, air-rotary, Rotosonic) as well as channel sampling. Diamond core drilling is recommended during the Characterization Program because it yields intact rock samples, allowing for accurate mineralogical, structural, and geochemical characterization of bedrock horizons (air-rotary methods are commonly used for drilling blast holes and the chips can be collected for verification testing during construction, as discussed in 7.6.5.1). This section will emphasize sampling considerations related to diamond core drilling such as: sample site selection and sample quantity, drilling and sample handling, core logging, sample selection, and preparation.

Quarry sources or any crushed bedrock from off-project sources should be assessed prior to on-site application starting with a desktop evaluation and field reconnaissance, as discussed in Sections 5.1 and 5.2. If field reconnaissance reveals the presence of PAG materials, then the source will either not be selected or be subjected to further characterization at the discretion of the QP during the Characterization Program.

5.4.2.1 Sample Location Selection and Quantity

No one-size-fits-all solution exists for selecting sample sites in PAG bedrock terrain since natural conditions and project needs will vary from project to project. Additionally, PAG risk tolerance amongst practitioners and the public may influence the scale of a sampling plan. For some excavation sites, prescriptive approaches to sample siting may be adequate whereas in complex geologic environments iterative approaches may be more appropriate. Consequently, the QP will be relied upon to navigate the sample siting process so that the testing results used to formulate the Mitigation Design for an excavation area are representative, useful and defensible.

Sample siting for drilling will initially be based on the minimum number of test samples needed to properly characterize the geochemical properties of the excavated volume. This approach is based on a statistical evaluation of the sample set obtained from the characterization plan for the Eagles' Nest Project, which required PAG rock mitigation for roughly 150 000 cy of rock excavation (Appendix D). The statistical evaluation used a technique adopted by Garvie and Kentwell (2017) to estimate sampling rates based on the distribution of sulfur data for a given rock type. Sample sets from a relatively homogeneous unit (a dacite porphyry) and from a deformed and vertically bedded (relatively heterogeneous) unit (Soudan Iron Formation) were examined, providing end-members to bound the sampling frequencies. The test sample frequencies in Table 5.1 are based on a 90% success rate of replicating the distribution, rounded to the nearest 100 cy. In general, for projects where multiple rock units or formations are intersected during excavation, at least one sample for each bedrock unit should be collected; detailed guidance for rock core sampling is discussed in 5.4.2.4.

Table 5.1 Minimum Requirements for Subsurface Bedrock Sampling

Lithology	Example Lithologies	Test Sample Frequency	Sample length	Over-break length
Massive, uniform, or laterally continuous rock types	Granite batholith, Duluth Complex, Biwabik Iron Formation	1 sample/600 cy of excavation volume	5 ft	5 ft
Bedded, deformed, or heterogeneous rocks	Virginia Formation, deformed iron formations, shear zones	1 sample/200 cy of excavation volume	3 ft	5 ft (<45 degree dip) 10 ft (>45 degree dip)

The minimum number of test samples for an excavation area will be based on the proposed rock excavation volume and lithology. The lithology will dictate the sampling frequency and sample length (see Table 5.1). For example, if site investigations reveal that massive igneous intrusions will be encountered for a 6 000 cy excavation then a minimum of 10 test samples (6 000 cy/600 cy), each 5 ft in length, will be required to properly characterize the excavation area.

The number of sample sites for an excavation area will also be based on the physical configuration of the proposed rock excavation. For a sample site within the example excavation area above, if the excavation depth is 10 ft, then two samples will be required from the sample site (10 ft/5 ft per sample). Since bedrock topography is likely to fluctuate within the excavation area, the number of samples per borehole will vary and, thus, an adjustment to the number of sample locations may be necessitated. Sample locations should be approximately evenly distributed throughout the excavation area, and at least one sample from each lithologic type represented should be collected. Field reconnaissance observations (bedrock dip, low areas, mapped faults, for example) and geophysical interpretations should also be factored into the locating process.

Once the sample sites are determined, each site must include an additional sample length below the proposed excavation grade, termed “over-break length” in Table 5.3. The over-break length will vary based on the pre-determined lithology. Samples from the over-break length will be in addition to the calculated number of test samples.

For steeply dipping and bedded lithologies, a single sample site will consist of a line of inclined holes oriented perpendicular to dip direction and sited across the excavation area to capture all bedding. For steeply dipping bedrock, a 10 ft over-break length will be applied.

5.4.2.2 Drilling and sample handling

During the drilling process, representative intact rock samples will be acquired from pre-determined sites and depths within the excavation area. The samples will be logged (Section 5.4.2.3) and tested (Chapter 6); the results of the testing will be relied upon to design the Mitigation Design. Since the Mitigation Design will impact construction schedule and cost, as well as long term effectiveness, it is important that high recovery samples are properly acquired, well documented, and handled properly in the field.

Proper sample acquisition will begin with pre-drilling field activities, including verifying location and assessing accessibility of pre-determined borehole locations. If borehole locations require re-locating, then the new location should be recorded by GPS or MnDOT Surveys. For inclined holes, instructions should be developed prior to drilling for establishing and recording azimuth and dip of inclined boreholes (see examples from Eagle’s Nest Project in Appendix B).

Drilling activities will be supervised by QP who will record information and observations in a MnDOT field boring log, following guidance found in the MnDOT Geotechnical Engineering Section manual. Personalized or company-specific field logs may also be used if approved by MnDOT. The QP must pay particular attention to water table and bedrock elevation as well as visible sulfide concentration during drilling. Core drilling will be performed using water and NQ-sized bits/barrels, unless otherwise approved by the QP.

Rock core will be handled by QP, following the MnDOT Geotechnical Engineering Section Manual for proper core box identification, depth delineation, and placement of rock core in the box. Core will be allowed to air dry prior to covering and will be protected from re-wetting or excessive humidity during transport and storage. Digital photos will be taken of the drill site and filled core box. Chain of custody will be documented between the drill site and the lab.

5.4.2.3 Rock Core Logging

A QP will prepare and log the core in accordance with the MnDOT Geotechnical Engineering Section Manual. At a minimum, the following information should be collected:

- Core interval, recovery, and RQD
- Formation/member name
- Rock type
- Degree of weathering/strength
- Color
- Grain size/texture
- Structure (bedding/foliation/banding, fractures, joints, orientation and density)
- Moisture content
- Visual sulfide estimate (see figure in Appendix B)

High-quality digital color photographs will be taken of all collected core or samples prior to storage or shipment to the laboratory.

5.4.2.4 Sample selection and preparation

All acidic, alkaline, and neutral materials require testing to assess the overall geochemistry of a site. Therefore, all core acquired for subsurface bedrock sampling will be tested; core recovered from overburden will be evaluated as described in Section 5.4.1.3. Core will be separated into samples based on the prescribed sample length for a given lithology (Table 5.1), starting at top of bedrock. Sample lengths (compositing) should not cross lithologic units. However, multiple sequential thin strata may be grouped into lengths up to three feet, except if a specific unit is suspected of high potential acidity. Analyze that specific stratum alone (do not combine with adjacent material). Individual samples with different color, texture, or fizz rating may not be combined to create a composite. Compositing is permitted for equal amounts of up to three vertically-adjacent samples. The individual samples making up the composite must represent equivalent strata thicknesses of identical material (all same rock type).

Samples that are longer than the predetermined sample length will be divided into equal lengths or divided using geologic judgement by a QP. Each sample length will be cut longitudinally with a water-cooled saw and allowed to air dry. All sample lengths designated for testing will be stored in appropriate containers and protected from moisture. All shall be properly labeled to allow for positive identification of the sample date, project, boring number, and depth increment. Retain unused half of the cut core in the original core box for future reference, analyses, or storage. If rock bedding or veining is steep to vertical such that a vertical split could jeopardize the representativeness of the sample then modify saw cutting to preserve geochemical characteristics of the sample length. Following splitting, the entire length of the split core is required to be crushed until all particles pass the #60 sieve (P60; 0.0098 in or 250 µm) as measured by AASHTO T 27. Crushed and sieved particles are to be thoroughly mixed to produce homogeneous and representative samples for each sample increment. A 12-inch length of split 2-inch diameter rock core yields approximately 1 to 1.5 pounds (500 to 750 g) of crushed sample.

5.4.3 Geophysics

Geophysics applies physical theory and measurements to understand earth properties. The properties of resistivity and chargeability are of particular interest in PAG environments since electrical anomalies in processed geophysical models can be indicative of sulfide presence. Performing electrical resistivity imaging and induced polarization surveys should be considered prior to drilling as a means of targeting soil and bedrock sample collection. Seismic surveys should also be considered, particularly where drill rigs have difficulty accessing sites where bedrock elevation needs to be determined. Survey geometries will be based on geologic observations and proposed depth of excavation which will, collectively, influence model resolution. Consequently, geophysical surveys should only be performed by qualified personnel with experience working in PAG environments.

CHAPTER 6: SAMPLE TESTING AND ANALYSIS

This chapter describes the laboratory analytical tests that are recommended for the characterization of PAG rock through acid-base accounting (ABA) and how to interpret the results of those tests to determine whether mitigation may be necessary. ABA is the term used to describe the procedures and calculations used to test and assess the potential for a material to generate ARD. The ABA procedures include a NP component as well as an AP measurement. The procedures were originally outlined by the U.S. EPA (Sobek et al. 1978). Since 1978, there have been numerous method modifications from the original U.S. EPA ABA procedures. The procedures recommended in this Guidance Document were selected as protective methods to characterize typical PAG rock encountered in northern Minnesota highway construction.

6.1 OVERVIEW OF ABA TERMS AND ASSUMPTIONS

Neutralization potential (NP) is a measurement of the capacity a material has for neutralizing acidity. Generally, NP is provided by carbonate and, to a lesser extent, silicate minerals (Section 3.2). Carbonate minerals providing NP commonly include calcite, dolomite, aragonite, magnesite, and ankerite. Silicate minerals are too numerous to list, but common silicates in northern Minnesota that are particularly important in providing NP include olivine and plagioclase. Carbonate neutralization is more effective for project construction timescales than silicate neutralization because carbonate minerals dissolve more quickly to provide the ions involved in the neutralization reactions (Section 3.2). Some methods of ABA testing may under-predict silicate NP by only considering carbonate NP, whereas other methods may over-predict silicate NP due to testing conditions that promote increased silicate dissolution relative to field rates. As indicated in Table 2.1, both carbonate and silicate minerals that provide NP are present in various geologic terranes in northern Minnesota. The method recommended to characterize the NP of the diverse geology of northern Minnesota, Sobek NP, is discussed and described in Section 6.5.

Acid-generating potential (referred to either as AGP or simply AP) is a measurement of the capacity a material has to produce acid, generally by the oxidation and dissolution of sulfide minerals. Because ABA was initially developed for the assessment of coal overburden, the original method assumes that all sulfur in an ABA material is representative of acid-generating pyrite (Sobek et al. 1978). However, in different geological environments, such as northern Minnesota, the assumption may be an oversimplification. In many natural materials, non-pyritic sulfur is present. Depending on its chemical composition, this sulfur can be acid-generating or non-acid-generating and can exist as different sulfur species (generally sulfide or sulfate in minerals; organic forms of sulfur might also be present). Inclusion of non-acid-generating sulfur in the AP calculation may lead to the over-prediction of AP; however, some sulfur speciation methods will incorrectly assign acid-generating sulfur minerals (e.g., melanterite, pyrrhotite) to the non-acid-generating fraction. The method recommended to provide a protective value for AP, MPA from total sulfur, is discussed and described in Section 6.6.

The units for AP and NP are tons of $CaCO_3$ equivalent per thousand tons of material, which can be abbreviated as tons per kiloton (T/kT). Units for NP and other ABA parameters are often reported in a variety of units that reflect one mass part of $CaCO_3$ equivalent per thousand mass parts of bulk material. Commonly used units also include tons per thousand tons, kilograms per thousand kilograms, and kilograms per (metric) ton. Generally, the use of "tons" in ABA refers to metric tons, but the T/kT values are equivalent for metric and short tons.

6.2 IMPLEMENTATION

As discussed in Chapter 5, bedrock and imported rock samples collected as part of the field reconnaissance will be screened for total sulfur and carbon via combustion-infrared spectrophotometer. Testing during the Characterization Program will involve effervescence and rinse pH/conductivity for soil samples and Sobek NP for rock core samples.

The methods for conducting these tests are described below.

6.3 SAMPLE PREPARATION

Samples, selected as described in Chapter 5, will be prepared and tested by a consultant lab or by MnDOT specialists following industry standards for quality control. The ABA testing protocols generally require that samples be dried and reduced to a specific particle size fraction. Drying procedures should not use high heat, as it may cause volatilization of sulfur- and carbon-bearing phases. Crushing and grinding of bulk materials (i.e., pulverizing, as described in EPA (2004)), is important in order to ensure a representative sample, but particle size can impact the reactivity of a sample (White, Lapakko, and Cox 1999). Particle size recommendations for testing may vary but generally include material passing through a range of #200 to #100 (P200 – P100), for a maximum particle size of between 0.0029 and 0.0059 inches (74 and 150 µm) (International Network for Acid Prevention 2014; ASTM International 2013b). Thus, consistent laboratory protocols are necessary to ensure that samples are representative and comparable. For the purposes of this Guidance Document, material passing through a #200 sieve should be used in tests that require materials to be pulverized.

6.4 SCREENING TESTS

Screening tests will be used to preliminarily assess PAG risk of bedrock prior to developing a more robust Characterization Program. Screening tests for bedrock samples will be performed during field reconnaissance activities and include total sulfur and carbon content (via combustion-infrared spectrophotometer). Soil screening tests will be performed during the Characterization Program or geotechnical/pre-design subsurface investigation and include dilute HCl application, paste pH and paste electrical conductivity for soil and other unconsolidated materials. These methods are referenced in Chapter 5.

6.4.1 Total Carbon and Sulfur via Combustion-Infrared Spectrophotometer for bedrock

Measurement of the total carbon and total sulfur contents is intended to screen whether or not proposed bedrock excavation areas or imported crushed bedrock will require additional characterization by the methods described later in this chapter.

Carbon and sulfur can be measured in an apparatus equipped with a combustion chamber, oxygen carrier stream, and infrared absorption detector (sometimes referred to as a LECO® furnace, after the brand name of one manufacturer of this type of instrument). Testing follows the method outlined in ASTM E1915 (ASTM International 2013b) and using procedures consistent with the instrument manufacturer's instructions. Carbon and sulfur test result interpretation is described in Section 7.7.

To prepare samples, a representative subsample from the hand sample will be split (via ASTM C702 or AASHTO T 248) and pulverized to pass the #200 sieve, according to ASTM 1915 (P200; corresponding to <0.0029 in or <74 µm) for screening testing.

The ASTM method lists the lower end of the quantitative range for total sulfur as 0.023%. Because detection or reporting limits may vary among instruments and laboratories, the lower limit of the quantitative range given in the ASTM method should be interpreted as the maximum value to which the "below detection" decision criteria in Table 6.1 apply. That is, a no mitigation or further evaluation decision based on total sulfur result that is 'below detection limit' must be based on an analysis with a detection limit of no greater than 0.023% sulfur.

6.4.2 Soil and Unconsolidated Overburden Screening

For soil and other unconsolidated materials, assessment will be conducted by a non-MnDOT QP during the Characterization Program by assessing effervescence via HCl and utilizing a rinse pH and conductivity test ("paste" test).

The classification of effervescence provides a ranking of the relative amount of available carbonate present in the material. Greater effervescence indicates a higher amount of carbonate. A small amount of dilute HCl is added to the sample, and the reaction is observed and ranked according to the classes in NRCS (2012). This test is similar to the fizz test step of the NP procedure described later in this chapter (Section 6.5.1).

The "paste" test is a type of paste pH and conductivity test. The test can be conducted in the field or in a laboratory. The procedure for this test is described in Section 11.6.5 of MEND (2009). A 1:1 mass ratio of sample and distilled or deionized water is mixed by shaking or stirring for approximately one minute, and then allowed to settle for approximately ten minutes. The pH, specific conductance, and, if possible, oxidation-reduction potential of the supernatant are measured.

The combined results of the desktop study, field reconnaissance, and screening tests will be interpreted by a non-MnDOT QP that will assess PAG risk and suggest further testing, if necessary. *De minimis* conditions mitigation measures may also be considered and follow guidance in 5.3.3.

6.5 NEUTRALIZATION POTENTIAL EVALUATION METHODS

If it is determined that a Characterization Program is necessary for assessing bedrock, further ABA analyses will be required. A sampling and testing plan will be developed with the assistance of non-MnDOT QP(s) as stated in section 5.3 and illustrated in Figure 4.2.

The NP of geologic materials is determined by calculating the amount of acidity consumed by the material. This Guidance Document recommends following a Sobek NP procedure, as outlined in Chapter 13.3.3 of MEND (2009), with the inclusion of a peroxide correction for siderite (when suspected to be present). The procedure is designed to measure NP from carbonate and reactive silicate minerals. The major steps for determining neutralization potential as outlined in this guidance are:

- Rating the approximate amount of carbonate NP based on a fizz test;
- Reacting the material with excess acid;
- Reacting the mixture with hydrogen peroxide, a strong oxidant (when siderite may be present); and
- Back-titrating with sodium hydroxide.

These steps are described below. The recommended procedure is outlined in further detail in Chapter 13.3.3 of MEND (2009), in Section 3.2.3 of Sobek et al. (1978), and in Section 10 of ASTM E1915 (ASTM International 2013b).

6.5.1 Fizz Test

The first step in most NP procedures is a fizz test, which is used to determine the amount and strength of acid added in the next step. A small amount of sample is treated with a drop or two of hydrochloric acid (HCl), and the amount of “fizz” resulting is visually rated by the analyst as none, slight, moderate, or strong. This rating is used to determine the amount and strength of acid used in the next step of the NP procedure. This method is detailed in in Chapter 13 of MEND (2009) and Section 3.2.3.5 of Sobek et al. (1978).

6.5.2 Reaction with Excess Hydrochloric Acid

A known amount of HCl is added to a sample of the material. The amount and strength of the acid are prescribed by the fizz test rating. The acid added should be enough to fully react all carbonate minerals. The mixture is heated until the reaction is visibly complete (no longer bubbling). This step and the subsequent titration should also be conducted on a blank (no solid material added) for use in the calculation described in Section 6.5.5. A full procedure for this method can be found in Section 13.3.3 of MEND (2009) and in Section 3.2.3 of Sobek et al. (1978).

6.5.3 Reaction with Peroxide (Siderite Correction)

The method used to correct for the presence of siderite is referred to as Peroxide Correction, Siderite Correction, SobPer, Skousen, or the Modified Sobek (a name used for several procedure modifications) procedure in literature and protocols. In this method, an extra step is added between the HCl reaction (Section 6.5.2) and sodium hydroxide (NaOH) titration (Section 6.5.4). Following the HCl reaction (Section 6.5.2) and cooling, the mixture is filtered, and hydrogen peroxide is added to the filtrate liquid. The solution is boiled again and then titrated with NaOH as described in the next section. This method is described in Skousen et al. (1997). If the project is located in a geologic region with no documented siderite, a QP can make the decision to eliminate this step.

6.5.4 Back-Titration with Sodium Hydroxide

The mixture is titrated to a set pH (7.0) with NaOH at a known concentration, which is the same as the concentration of the HCl in the previous step (Section 6.5.2). This method is described in Section 13.3.3 of MEND (2009) and in Section 3.2.3 of Sobek et al. (1978).

6.5.5 Calculation

Based on the results of the titration, the NP is calculated using the following formula:

Constant (C) = (mL acid in blank)/(mL base in blank)
mL acid consumed = (mL acid added) – (mL base added) x C
NP = (mL acid consumed) x (normality of acid) x 25.0

Equation 5

see footnote 2

6.6 ACID-GENERATING POTENTIAL EVALUATION METHODS

The AP of geologic materials is determined by measuring the amount of sulfur-bearing minerals that are present in the rock. As described in Chapter 3 and in Section 6.1, not all sulfur-bearing minerals are acid-generating; however, some sulfur speciation methods will incorrectly assign acid-generating sulfur minerals to the non-acid-generating fraction. Therefore, a protective AP should be estimated using MPA from total sulfur. If ABA results are uncertain, sulfur speciation and/or additional methods to better define AP can be used (Section 6.9).

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[2] $$X\frac{\text{mL acid added}}{\text{2 g material}}\times N\frac{\text{eq}}{\text{L acid}}\times\frac{\text{1 L}}{\text{1000 mL}}\times\frac{\text{1 mol CaCO3}}{\text{2 eq}}\times\frac{\text{100 g CaCO3}}{\text{1 mol CaCO3}}\times\frac{\text{1 T CaCO3}}{10^6\text{g CaCO3}}\times\frac{10^9\text{g material}}{\text{1 kT material}}=\frac{10^{11}}{4\times10^9}=X\times N\times 25\frac{\text{T CaCO3}}{\text{1 kT material}}$$

where X is the amount of acid consumed and N is the normality of the acid. *T* refers to metric tons, 1,000 kg.

The recommended procedure for AP is to measure the weight percent sulfur in a sample by combustion, such as by ASTM E1915 (ASTM International 2013b) or as detailed in Sobek et al. (1978).

To calculate AP, the total sulfur content should be converted to tons of calcium carbonate equivalent per thousand tons of material, or tons per kilotons (T/kT):

$$AP = S \text{ (wt. \%) } x\ 31.25$$ **Equation 6**

Examples of this calculation are included in Section 7.4.2.1.

$$X \times \frac{\text{g S}}{\text{100 g material}} \times \frac{\text{1 mol S}}{\text{32 g S}} \times \frac{\text{2 eq}}{\text{1 mol S}} \times \frac{\text{1 mol CaCO3}}{\text{2 eq}} \times \frac{\text{100 g CaCO3}}{\text{1 mol CaCO3}} \times \frac{\text{1 T CaCO3}}{10^6\text{g CaCO3}} \times \frac{10^9\text{g material}}{\text{1 kT material}} =$$
$$X \times \frac{2\times10^{11}}{6.4\times10^9} \frac{\text{T CaCO3}}{\text{kT material}} = X \times 31.25 \frac{\text{T CaCO3}}{\text{kT material}}$$ **Equation 7**

where X is the sulfur content of the material in weight percent.

6.7 NET POTENTIAL CALCULATIONS

Once determined, the NP and AP values are evaluated relative to each other to assess whether a material has the potential to be acid-generating. Examples of these calculations are included in Section 7.4.2.1.

6.7.1 Net Neutralization Potential

The net neutralization potential (NNP) is given by:

$$NNP = NP – AP \text{ (in units of T/kT)}$$ **Equation 8**

This value can be used to estimate the amount of neutralization capacity that needs to be added to a system to prevent acid drainage. Generally, a positive value suggests a net neutralizing material, and a negative value suggests a net acid-generating material. A positive value indicates the amount of excess neutralization capacity, and a negative value indicates the amount of neutralization capacity that would need to be added to prevent acid drainage. However, there is an amount of uncertainty in these measurements (e.g., varying precision in the analytical methods, geologic variability), and NNP sign should not be used as the sole criteria for identifying a system as unlikely to be acid-generating, particularly at high values of NP and AP. NNP does not give a full picture of the relative amounts of NP and AP; therefore, net potential ratio (NPR; Section 6.4.2) is more commonly used as a determinant (International Network for Acid Prevention 2014); this Guidance Document includes thresholds based on both measurements.

6.7.2 Net Potential Ratio

The NPR is given by:

$$NPR = NP/AP \text{ (unitless)} \quad \text{Equation 9}$$

The ratio between NP and AP is also used to estimate whether a material will produce acid drainage. A ratio below 1.0 suggests that the material is acid-generating, whereas a higher ratio suggests that the material is non-acid-generating. Because there is uncertainty in the analysis, an NPR of >1 may not definitively indicate a non-acid-generating material, particularly at low values of NP and AP. Results must be interpreted in conjunction with NNP values.

6.8 INTERPRETATION

Due to the many sources of uncertainty in the ABA results and interpretation as well as the heterogeneity in natural weathering environments, margins of safety must be considered in assigning a material as PAG or non-PAG material. As noted above, NNP = 0 and NPR = 1 are theoretical thresholds between acid-generating (lower values) and non-acid-generating (higher values) materials, but these values do not incorporate protective margins. Varying guidance exists for cutoff values of NNP and NPR above which materials are considered to be non-PAG. In some cases, speciated sulfur concentration, paste pH, NAGpH, and/or kinetic test results may be used as additional decision path elements. In most cases, threshold values are accompanied by allowances for additional interpretation of the mineralogical context and risk considerations of the project by a QP. Recent MnDOT work at Eagles' Nest incorporated a mitigation threshold of NPR < 3 (Golder Associates Inc. 2016). For consistency, this threshold value is carried over into this Guidance Document. In addition, a NNP threshold of 24 T/kT is incorporated based on the Pennsylvania and Tennessee guidance documents (Pennsylvania Department of Transportation 2015; Golder Associates Inc. 2007). Pennsylvania gives an initial target NNP level of 12 to 20 T/kT with a safety factor of 2, and Tennessee lists a value of 12 T/kT based on the work of the Acid Drainage Technology Initiative. The value of 24 T/kT incorporates an NNP of 12 T/kT and a factor of safety of 2.

Threshold values are used to separate material into three classifications: PAG material, uncertain material, and non-PAG material (Table 6.1 and Figure 6.1). PAG material is likely to generate acidity and requires mitigation measures. Mitigation is detailed in Chapter 7. Uncertain material can be treated as PAG material or may be subjected to additional testing to more precisely assess its likelihood of acid generation, as outlined in Section 6.9. These tests may be particularly appropriate for large-scale projects that would have significant mitigation costs. Non-PAG material does not require any mitigation for acidity.

Section 5.4 discusses conditions under which samples from different lithologies may and may not be composited for analysis. Samples that are not composited are analyzed individually according to the procedures described in Sections 6.5 to 6.7. Among these samples, there may be variable results, with results from some units indicating PAG material and others indicating non-PAG material. In these instances, the project should proceed to mitigation to account for the PAG sections. The Mitigation Design for the project should be developed with consideration of all rock types.

If all samples collected as part of the Characterization Program (Section 5.4) are classified as non-PAG, the findings will be documented and submitted to MnDOT Geology Unit and the Project Manager, indicating that the project may proceed without further inquiry.

If any materials from the project classify as either uncertain or PAG, a potential for acid generation exists and further consideration of the results within the context of the project will take place.

The classification of materials as uncertain warrants an evaluation of the cost-effectiveness of mitigation without further characterization (i.e., mitigating with the assumption that the material is PAG). If mitigation is cost-effective for the project, a Mitigation Design and a Monitoring Plan will be developed (Chapters 7 and 8). If mitigation and treatment are likely for the project, regulatory agency discussions and review may be necessary. These consultations can be arranged at the Project Manager's discretion or under the jurisdiction of the applicable permitting authority (e.g., stormwater management or wetland permitting). If mitigation is not cost-effective, additional data collection, as described in Section 6.9, will take place to provide a basis for interpretation and further refinement of material classification.

The classification of materials as PAG indicates that a Mitigation Design and Monitoring Plan will be necessary.

Table 6.1 Acid-base accounting results screening guidance for MnDOT Districts 1 and 2

Material Type	Net Potential Ratio, NPR	Net Neutralization Potential, NNP (T/kT)	Outcome
PAG Material	< 1	< 0	Mitigation (Chapter 7)
Uncertain Material [3]	1 – 3	0 – 24	Additional testing (Section 6.9) and/or mitigation (Chapter 7)
Non-PAG Material	> 3	> 24	No special handling required

[3] Uncertain material also includes material with NPR > 3 and NNP < 24 T/kT, or NPR < 3 and NNP > 24 T/kT.

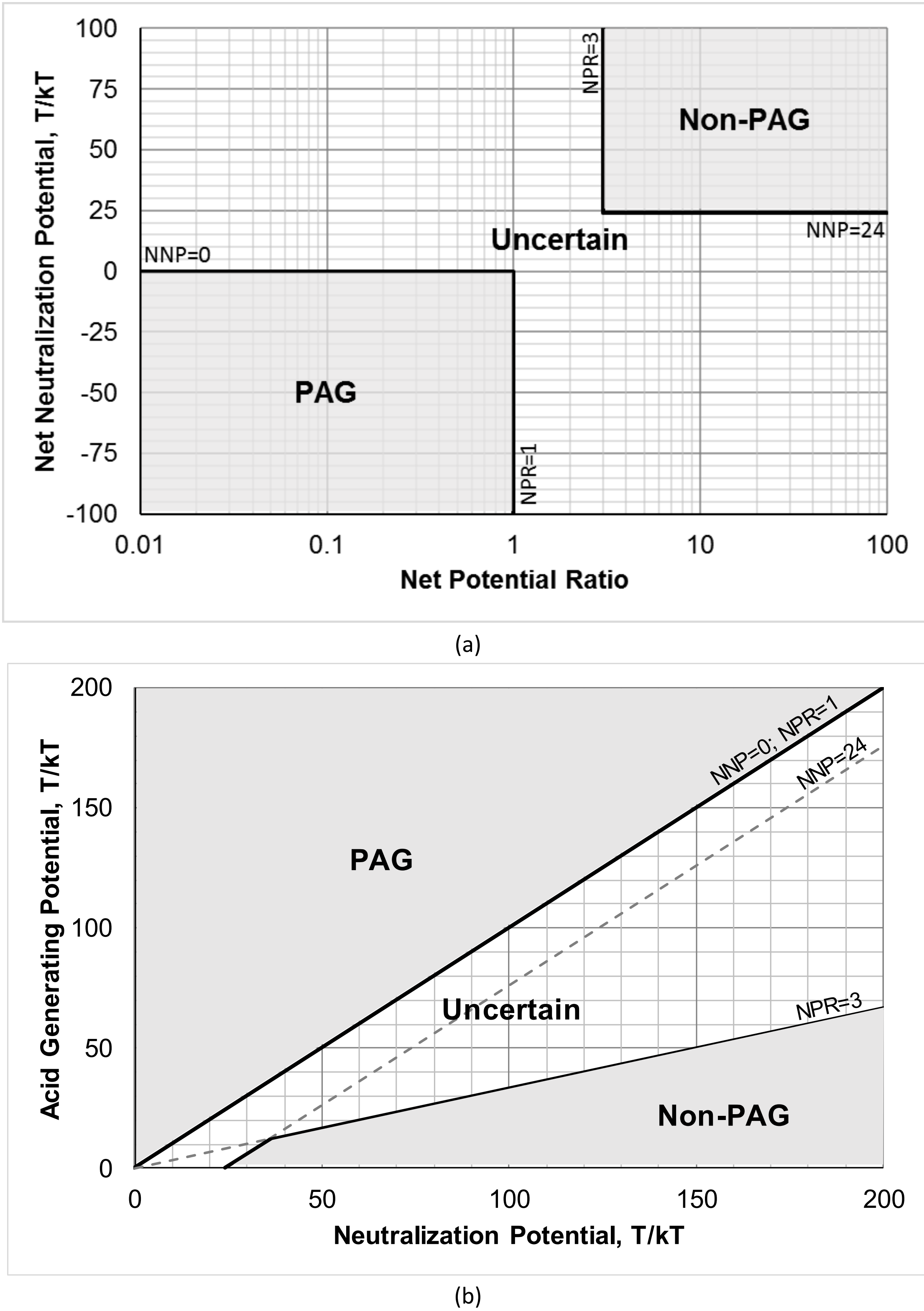

Figure 6.1 Plots showing PAG, non-PAG, and uncertain classifications for (a) NPR and NNP and (b) NP and AP.

6.9 ADDITIONAL ANALYSES

In some scenarios, ABA yields inconclusive results, classified in Table 6.1 as uncertain materials. In these instances, additional tests and indicators can provide more information. These tests may be more expensive and/or time consuming than the initial ABA tests, but they may also serve to reclassify uncertain results as either PAG or non-PAG, potentially decreasing mitigation costs, particularly on large-scale projects. The results of these tests may also inform mitigation measures (Chapter 7). The design and interpretation of these tests should be overseen by a QP.

6.9.1 Theoretical Considerations of ABA

One method sometimes used as a measure of NP is based on an analysis of total carbonate by combustion, which is the difference between total carbon and HCl-insoluble carbon (or sometimes other extraction techniques) from combustion-infrared spectrophotometer measurements (ASTM International 2013b). However, due to specific geological considerations present in northern Minnesota, as described in the next two paragraphs, this method may not be appropriate for many projects.

An important consideration in measuring NP in northern Minnesota is the presence of siderite in many sulfide-bearing geological materials (Chapter 2). Siderite is an iron (II) carbonate ($FeCO_3$). When it dissolves, it produces carbonate, which can neutralize acid and ferrous iron (Fe^{2+}), consuming acidity as it oxidizes to ferric iron (Fe^{3+}). This therefore can precipitate as ferric hydroxide ($Fe(OH)_3$), consuming alkalinity. The manganese carbonate mineral rhodochrosite can undergo a similar process. This net process (in the presence of oxygen) neither generates nor neutralizes acidity. However, because these reactions occur at different rates and are affected by the conditions of the NP procedure, the presence of siderite can result in over-prediction of NP. To account for this process, the NP method used when siderite is likely to be present must include a peroxide correction step to rapidly oxidize ferrous iron to ferric iron (Section 6.5.3), such as described by Skousen et al. (1997), and cannot be based on a measurement of total carbonate.

Another important consideration in measuring NP in Minnesota is the presence of graphite in metamorphic rocks. Graphite is a native carbon mineral. It is not acid-generating or neutralizing. However, when NP is characterized through total or speciated (by pyrolysis) carbon concentrations, graphite can be misreported as carbonate carbon, increasing the reported NP value. Thus, an NP titration procedure, as described in Section 6.5, may be more appropriate.

As described in Section 6.1, AP in this Guidance Document is calculated as MPA based on total sulfur. However, not all sulfur is acid-generating, and methods exist to separate sulfur forms in analysis. These methods do not always effectively separate acid-generating phases from non-acid-generating phases, which is why this Guidance Document recommends testing for MPA. When initial ABA results are inconclusive and geologic information suggests that non-acid-generating sulfur is present, sulfur speciation methods can be used to more accurately assess AP. For example, mining guidance from

Nevada requires sulfur speciation for NPR results below 1.2 (Nevada Division of Environmental Protection, Bureau of Mining Regulation and Reclamation 2015).

6.9.2 Sulfur Speciation

There are a number of methods to evaluate different forms of sulfur; the most appropriate of which depend on the particular material being analyzed. Common methods can be found in the ASTM standard E1915 (ASTM International 2013b), reports by the Mine Environment Neutral Drainage program (Mine Environment Neutral Drainage (MEND) and Canada Centre for Mineral and Energy Technology 2001; Coastech Research Inc 2008; MEND 2009), and others (e.g., Sobek et al. 1978; White, Lapakko, and Cox 1999; International Network for Acid Prevention 2014).

Pyrrhotite is an iron sulfide found in some northern Minnesota rocks (Chapter 2). If geologic information indicates the potential presence of pyrrhotite, HCl-insoluble sulfur, the most common method used to speciate sulfide sulfur, should not be used as a measurement of sulfide sulfur, as pyrrhotite is HCl-soluble.

If modified sulfur characterization testing reviewed by a QP results in NPR and NNP values greater than 3 and 24 T/kT, respectively, the material can be classified as non-PAG.

6.9.3 Paste pH

Testing for ABA is often accompanied by measurement of paste pH (EPA 2004). Paste pH is measured by mixing equal amounts (by mass) of a solid material (e.g., soil or crushed rock) and deionized water, allowing the mixture to settle, and measuring the pH of the solution. The electrical conductivity or specific conductance of the solution can also be measured. This test can be conducted in a laboratory or in the field, making it a useful screening tool for identifying PAG rock. However, paste pH accounts for only short-term reactions and may not provide an accurate representation of longer-term behavior of materials. Therefore, paste pH alone should not be used to classify a material as PAG or non-PAG, but acidic paste pH in combination with an ABA uncertain classification indicates that a material is likely PAG.

6.9.4 NAGpH

Another pH screening test is the net acid generation pH (NAGpH, also referred to as a single addition NAG test). In this test, hydrogen peroxide is added to a sample that is then heated after any effervescence subsides, and the pH of the reacted mixture is measured (Ian Wark Research Institute and Environmental Geochemistry International Pty Ltd 2002). The hydrogen peroxide rapidly oxidizes PAG phases, resulting in a pH reading that may be a more accurate representation of the longer-term PAG characteristics of the material than a paste pH (Section 6.9.3) measurement. Results of this test may be interpreted similarly to those of paste pH; acidic NAGpH (<4.5; MEND (2009)) in combination with an ABA uncertain classification indicates that a material is likely PAG.

6.9.5 Mineralogical Testing

Another method for determining the sources of sulfur in a material is through mineralogical testing. This testing can include characterization by X-ray diffraction (XRD), optical and scanning-electron microscopy, electron probe microanalysis, and automated mineralogy (Lapakko 2002; Jambor, Dutrizac, and Raudsepp 2006; Parbhakar-Fox and Lottermoser 2015; Dold 2017). These techniques can be qualitative, quantitative, or a combination. Identification of major and minor sulfur-bearing minerals can indicate whether they are acid-generating. If significant amounts of non-acid-generating sulfur minerals are found, samples may be retested using appropriate sulfur speciation techniques, such as those described in Section 6.9.1, to refine the ABA results.

Some of these methods can provide a quantitative summary of the mineralogical and, in some cases, sulfur composition of a sample, though these techniques are based on limited amounts of material and may thus require a large number of analyses to be representative of a bulk material (Parbhakar-Fox and Lottermoser 2015). The results of quantitative mineralogical analyses can be used to calculate ABA values (NP, AP, NPR, NNP) that account for the specific sulfur- and carbonate-bearing minerals present in the material (Dold 2017) by a QP.

Mineralogical characterization using microscopy methods can also provide information about the likely reactivity of some minerals. For example, chemical weathering can result in the formation of secondary mineral phases on mineral surfaces. These secondary minerals can inhibit the reactions that lead to acid production and/or neutralization. The long-term effects of secondary mineral rinds and/or surface coatings may be assessed through kinetic testing (Section 6.9.6).

6.9.6 Kinetic Testing

Experimental testing of the behavior of a material over time is known as kinetic testing. Kinetic tests can be used to estimate the likely drainage chemistry from a particular material and its evolution over time as reactions with different kinetic rates proceed, secondary mineral phases form, and sources of various constituents are depleted. Common kinetic testing methods used in PAG rock assessment include humidity cells and column tests (International Network for Acid Prevention 2014). These tests generally consist of a cylinder filled with material that receives periodic (humidity cell) or continuous (column) additions of water that is collected for analysis from an outlet after percolating through the material. Humidity cell testing on various types of rocks from Northern Minnesota has been conducted extensively by the Minnesota Department of Natural Resources over several decades (Lapakko and Antonson 2012). Method details can be found in ASTM Method D5744 (ASTM International 2013a). Interpretation of this type of testing must be overseen by a QP.

6.10 QUALITY CONTROL SAMPLES

Quality control (QC) samples should be handled in the same manner as the sample group for which they are intended (i.e., stored and transported with the sample group). It is recommended that field (masked or blind) duplicate samples be collected in the field every 20 samples (5%) and submitted to the analytical laboratory. A field duplicate sample consists of a second aliquot of a sample collected at the same time as the original/source sample using the same procedures, equipment, and types of containers as the required samples. The samples are collected by alternating sampling containers from the original sample to the field duplicate sample (using the same exact methods for both). The field duplicate sample is identified with an alias (e.g., FD) on the sample container label and on the COC to keep the source of the field duplicate unknown to the laboratory. The time collected should be omitted on this sample also. Analyses of field duplicate samples are the same as the original project samples and give a measure of the precision associated with sample collection, preservation, and storage, as well as laboratory procedures. Field duplicate sample results are evaluated by calculating the relative percent difference (RPD) and comparing to project criteria.

$$RPD = \frac{|S-D|}{(S+D)/2} \times 100$$

Equation 10

Where: RPD = relative percent difference

S = original sample result

D = duplicate sample result

In addition, the analytical laboratory should perform duplicate analyses on 5% of the samples submitted. Samples should be analyzed at a certified/accredited laboratory (if applicable) with appropriate quality assurance and quality control methods.

CHAPTER 7: MITIGATION AND TREATMENT

This chapter describes mitigation and treatment concepts and design considerations. For the purpose of this Guidance Document, mitigation refers to the prevention or minimization of acid generation and the associated metal and anion loading to the environment. Treatment refers to the remediation of water discharges, effluents, or groundwater and the reduction of dissolved constituent loading to the environment by mass removal. This chapter approaches mitigation and treatment associated with soil and borrow materials as well as rock. Design and implementation of mitigation measures should be assisted by a qualified consulting firm or QP.

7.1 MITIGATION

Mitigation may include amendments to increase NP, isolation, or a combination of both. It is focused on preventing, minimizing, and/or eliminating the drivers of ARD. Prevention or minimization of these reactions can be achieved to varying degrees by avoiding PAG materials, or by minimizing exposure to moisture and the supply of oxygen to the materials. Specific design concepts, construction methods, and contract language associated with implementation are important factors in support of mitigation efforts, as discussed subsequently in this PAG Guidance.

Any constructed features intended to prevent, mitigate, or otherwise treat ARD or ML need to be recorded in the Geotechnical Asset data layer of Georilla to provide an administrative mechanism for documenting the location and for inspections or maintenance.

7.2 MITIGATION DESIGN CONCEPTS: AVOIDANCE

Avoidance refers to incorporation of design considerations to avoid disturbing PAG material. Options for avoidance may include modifications to grade, alignment, or depth of disturbance. Other modifications to design features may include redesign of utility crossings and exit/entrance ramps.

7.3 MITIGATION DESIGN CONCEPTS: ISOLATION

Several design concepts focus on isolating the PAG materials from moisture, sources of which include infiltration of meltwater and precipitation, stormwater runoff, and groundwater fluctuations. Isolation from oxygen is also an option in limited circumstances for roadways.

7.3.1 Isolation of PAG Material

To isolate PAG material, approaches often include covering PAG material with a durable, impermeable geomembrane to prevent infiltration of water and minimize diffusion and air exchanges associated with barometric pressure modulation. Protective non-woven geotextile and underlying subsoil placement between the angular PAG material and the geomembrane provide additional durability and protection during construction activities. Due to the cost of impervious materials used to cover the PAG material, it is often cost-effective to consolidate PAG material into a focused area, referred to as a repository or consolidation area. For most transportation projects that are located within a right-of-way that is narrow in width, the optimal location for the consolidation area is under the drive surface.

In some situations, oxygen transport may be limited by storage of the PAG materials under water in conditions of limited inflow/outflow. However, in addition to ownership and space considerations, significant regulatory constraints and permitting requirements must be considered, including floodplain, wetland, and surface water quality. Mine settings, such as pit lakes, differ from shallow surface water bodies in terms of their flushing rates and vertical trophic zones and thus can provide potential locations for sub-aqueous disposal of PAG material.

Alternatively, isolation from direct contact with water involves site-specific evaluation of localized hydrogeologic setting, including understanding seasonal variability of flows and groundwater elevations in pre-construction conditions. The purpose of understanding the seasonal maximum groundwater elevation is to constrain the design such that the lowest consolidated PAG material layer is at least five feet higher than the seasonal maximum groundwater elevation, in order to prevent upwelling of groundwater into the consolidated PAG materials. Site-specific understanding of stormwater management and future (post-construction) flow regimes is also important to minimize potential for infiltration into the PAG consolidation area.

Figure 7.1 illustrates a conceptual design for isolation of PAG under a roadway. Design details include mixing of neutralizing material with PAG material, placement of a granular soil layer over the sideslopes and top of PAG material, overlain by geotextile and geomembrane, topped with topsoil for sideslope vegetation and stabilization. The geomembrane may also be installed in an overlapping fashion within the sideslopes to prevent soil sliding along the geomembrane surface. The design also includes a minimum vertical separation between the bottom of the PAG material repository and the top of the seasonally-highest groundwater elevation.

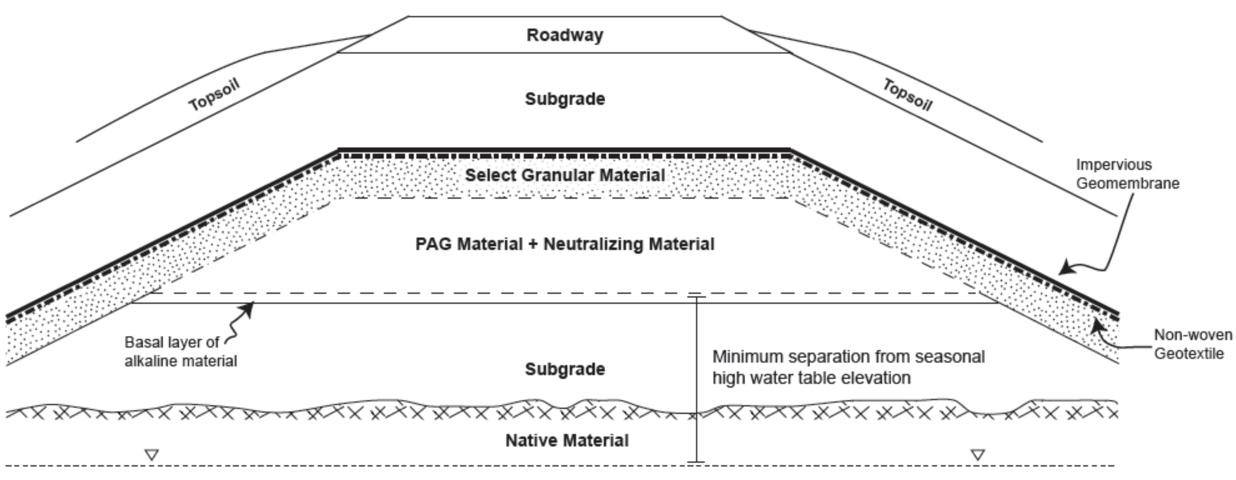

Figure 7.1 Typical PAG repository under roadway – design features.

7.3.2 Cover Materials

Typical characteristics of cover materials are described below; specifications for materials will be based on project-specific considerations. Additional information regarding cover materials and cold weather applications may be found in MEND's Cold Regions Cover System Design Technical Guidance Document (cold-climate July 2012 (Mine Environment Neutral Drainage (MEND) 2012). Many of the cover discussions in the MEND guidance are specific to open covers, rather than incorporating the geotechnical considerations associated with an overlying highway. This Guidance Document focuses on PAG repositories located under a roadway; however, additional approaches for covers of a PAG repository outside of a roadway exist, such as a geocomposite clay liner, compacted clay covers, and storage-and-release covers that use evapotranspiration to avoid infiltration of precipitation.

7.3.2.1 Geomembrane

The characteristics of geomembrane for use as an impervious cover are generally related to durability and permeability. Specific characteristics include permeability, thickness, tensile strength, tear resistance, puncture resistance, coefficient of lineal expansion, and low temperature brittleness. Frictional properties and texture of membrane surfaces are also important for preventing sliding of overlying soils (geogrid can be applied to membrane applications to reduce sliding potential). Stability analyses should be considered prior to finalizing designs which incorporate geomembrane. A QP or registered engineer should be sought to specify the most suitable membrane and draft special provisions for the project. An example specification from a geomembrane manufacturer is included for reference and consideration in Appendix E. Topsoil and slope-stabilizing vegetative grasses are required to protect the geomembrane from surface punctures and solar degradation. The purposes of a geomembrane in this Guidance Document include:

- **Impermeability**: prevention of water infiltration into the PAG material underlying the geomembrane; and
- **Durability**: including tensile strength, chemical resistance, puncture resistance, tear resistance, and low temperature brittleness; goal is to have a durable, competent overlying barrier.

The project engineer should ensure that an adequate quantity of geomembrane is available during construction to prevent over-exposure of PAG materials.

7.3.2.2 Geotextile

Typical characteristics of geotextile for use as a protective layer include durability in a variety of chemical environments, tensile strength, thickness, hydraulic conductivity/permeability, and flexibility. The MnDOT specification for geotextile is included as Appendix F use Type 5 for segregation of these materials. The purposes of the geotextile in this guidance include:

- **Separation** of the soil overlying angular PAG material from the geomembrane (protection and separation);

- **Permeability**, to avoid creating hydrostatic pressure which may contribute to geotechnical slope failure issues; and
- **Durability** in a variety of physical and chemical environments, to maximize product life.

7.3.3 Rock Faces/Slopes

In certain conditions, freshly-exposed steep rock faces can also be isolated from oxygen and water using a surface treatment such as shotcrete, which is a sprayable concrete product intended to adhere to the surface and harden into a durable concrete material. The presence of groundwater seeps on the face of the rock and/or evidence of previous groundwater or seasonal discharges are indicators that this approach may not be feasible, as water will deteriorate the surface treatment's bond to the rock wall. Minnesota's winter climate can also create issues for rock face isolation, as snow and other precipitation can negatively affect surficial adherence and isolation efforts. Shotcrete is an option for road cuts that are devoid of groundwater seeps or discharge.

For steep rock faces with evidence of groundwater or seasonal discharges that would render shotcrete ineffective, it may be appropriate to leave the rock surface exposed. In these situations, neutralizing materials may be placed in the areas underlying the rock face, and in the ditch in the direction of drainage. Mitigation considerations for these discharge areas are discussed in Section 7.7.2.

Other options for gentle rock slopes (i.e., 3:1 H:V) may include covering the slope with a soil layer, neutralizing materials, and a geomembrane; sometimes with additional anchoring or other means of minimizing potential for creep or slope failure of the along the geomembrane surface.

7.4 MITIGATION DESIGN CONCEPTS: NEUTRALIZATION

Designs for isolating PAG material often include the addition of material to provide neutralization capacity to offset the acid-generating capacity of the PAG material. In concept, the neutralizing materials are meant to neutralize anticipated acid generation from disturbed material resulting from exposure to oxygen and moisture as well as for exposure resulting from construction-related blasting and material handling. Typical neutralizing materials include calcite ($CaCO_3$), found in limestone, and agricultural lime, a commercially available fine-grained soil additive containing reactive calcium carbonate and calcium hydroxide.

PAG materials may be identified in close proximity to neutralizing materials that are naturally occurring in the bedrock, such as carbonate mineral formations (e.g., calcite, limestone, etc.). In cases where project activities will include excavation or disturbance of carbonate minerals or other minerals with rapid neutralization capability, mixing of the PAG material and natural neutralizing materials may reduce or eliminate the need for supplemental neutralizing materials. Minerals with slower-rate neutralization capability such as olivine and plagioclase are not appropriate for consideration as neutralization materials in this context.

7.4.1 Alkaline material placement locations

There are two areas in which alkaline material addition is appropriate. The first is a basal alkaline layer that may underlie the consolidated PAG that comprises the repository. The second is within the mixture of PAG material and supplemental alkaline material (SAM).

The basal layer of alkaline material should consist of a rapidly-neutralizing material, such as limestone, in the smallest practicable lift (generally less than six inches thick). This permeable basal layer is meant as a safety feature to augment the SAM that is mixed with the PAG, based on PAG characteristics, and as described below. The basal alkaline material is not part of the SAM; both contribute to the total amount of neutralizing material needed for a project.

Total Project alkaline material = SAM for mitigation + basal alkaline material

7.4.1.1 Basal alkaline material volume determination

The repository volumes and surface areas will be developed in coordination with the project design engineers, as a component of balancing cut/fill volumes during the design process. For a given project, the design team will need to incorporate both the basal alkaline material and the SAM mixed with PAG in their grading plans.

Depending on the PAG characteristics, the repository layout and the thickness of PAG material placement in the repository, the basal layer of SAM may be similar in volume to the SAM required for mixing and treatment of the PAG.

7.4.1.2 SAM material volume calculation considerations

The amount of neutralizing material to be mixed within the PAG repository is based on the PAG material characteristics determined in field and ABA testing as well as other supplemental testing, as needed (Chapters 5 and 6).

Key assumptions for all the following example calculations include use of a safety factor of 2, and an assumption that the bulk mixing of SAM adequately distributes the SAM within the PAG matrix. The safety factor is intended to address variability in sample representativeness, inefficiencies in mixing, and other factors unaddressed in this guidance such as microbial impacts on acid generation. The NNP goal is a minimum of 12 (Section 6.8), prior to application of the Factor of Safety.

Additionally, field modifications for neutralizing material dosing rates may be required based on moisture content of the SAM. The calculations in 7.4.2 present examples for determining the appropriate amount of SAM in a variety of situations.

7.4.2 Neutralizing amendments calculations

Calculations for SAM will be reported in “calcium carbonate equivalent” (CCE). Based on the properties of the neutralizing material selected for amendment, an adjustment must be made to calculate a CCE for the specific material used. This value is commonly provided on agricultural products, and can be determined from typical agricultural analyses for non-commercial products.

The grain size and angularity of neutralizing materials are directly related to specific surface area of the material (see Chapter 3). Maximizing surface area increases the availability of NP per unit volume of neutralizing material. Smaller grain sizes have higher specific surface area than coarser-grained particles. However, smaller grains are more easily eroded or displaced due to precipitation, wind and storm water runoff. Considering competing factors such as material handling, erosion potential, iron cementation, and treatment effectiveness, a mixture of agricultural lime (finer-grained particles) and crushed limestone (coarser-grained particles) is recommended for use as neutralizing materials, with angular to subangular particles. The mixture ratio of limestone to agricultural lime is generally 50/50, but the intention of the approach is to have particle sizes of SAM that approximate the particle sizes of the PAG material. The goal of the neutralizing material addition is to reach an NNP of at least 12 prior to application of a safety factor of 2 (Section 6.8). Mixing ratio determinations should be made by a QP.

7.4.2.1 Borehole result interpretation for SAM

ABA results from coring and drilling will vary among the strata sampled. Interpretation of the geologic data includes determining an NPR for an interval, typically associated with the thickness of the geologic material to be removed (see Section 5.3 for general guidelines for interval selection). Determining a NPR value for an interval is achieved by using a weighted average of ABA results, as demonstrated in Table 7.1.

Table 7.1 Example borehole calculations

Boring Depth (ft)	Thickness (ft)	Fizz Test	Total Sulfur (%)	NP (T/kT)	MPA (T/kT)	Fraction of Thickness	NP_w (T/kT)	MPA_w (T/kT)
NA	NA	NA	NA	NA	Total S × 31.25	Interval/Total Thickness	Fraction Thickness × NP	Fraction Thickness × MPA
0-1.5	1.5	Soil	Soil	Soil	Soil	Soil	Soil	Soil
1.5-4.5	3.0	sl	0.09	31	2.8	11	28.2	0.12
4.5-6.0	1.5	sl	0.07	34	2.2	16	31.8	0.06
6.0-9.0	3.0	n	0.25	4	7.8	0.51	-3.8	0.12
9.0-11.0	2.0	n	0.11	11	3.4	3.2	7.6	0.08
11.0-13.0	2.0	n	0.09	7	2.8	2.49	4.2	0.08
13.0-15.5	2.5	n	0.07	0.2	2.2	0.09	-2.0	0.10
15.5-18.5	3.0	n	0.18	0.1	5.6	0.02	-5.5	0.12
18.5-20.5	2.0	n	0.16	0.3	5.0	0.06	-4.7	0.08
Total	25	NA	NA	NA	NA	100%	4.1	8.4

NA – not applicable

$$NPR_{borehole} = (4.1\ T/kT)/(8.4\ T/kT) = 0.49\ (<1 \text{ – indicates PAG material})$$ **Equation 11**

$$NNP_{borehole} = (4.1\ T/kT - 8.4\ T/kT) = -4.3\ (<0 \text{ – indicates PAG material})$$ **Equation 12**

Results from this sample borehole calculation indicate the materials sampled and analyzed are considered PAG materials.

Note that the overburden, denoted above as ‘soil’, will be removed and re-used onsite, was not included in the PAG evaluation. Evaluation of overburden is described in Section 5.4.1.

Multiple borehole calculations:

For most projects, data will be collected from multiple boreholes or outcrops. The calculations summarized in Table 7.1 will be repeated for each borehole or outcrop data package. The combined evaluation of those data includes consideration of the volume of material represented, as shown in Table 7.2.

Table 7.2 Multiple borehole or outcrop sample interpretation

Borehole / Outcrop ID	Thickness of Borehole/ outcrop	NPw	MPAw	Percent of total project volume represented	NPw-area	MPAw-area
B-1	26.5	4.1	8.4	42%	1.733	3.55
OC-1	4	2.1	0.12	6%	0.13	0.007
B-2	20	2.4	12	32%	0.77	3.84
B-3	12	0.2	40	19%	0.038	7.68
Sum:	NA	NA	NA	100%	2.67	15.1

NA – not applicable

In this example,

$$NPR_{area} = (2.67\ T/kT)/(15.1\ T/kT) = 0.17\ (<1 – \text{indicates PAG material})$$ **Equation 13**

$$NNP_{borehole} = (2.67\ T/kT – 15.1\ T/kT) = -12.4\ (<0 – \text{indicates PAG material})$$ **Equation 14**

This project area would be considered PAG material.

7.4.2.2 Example Calculations for SAM dosing

This section provides calculation examples for determining the amount of SAM needed for mitigation of PAG.

EXAMPLE 1 – SINGLE ROCK TYPE

This example calculates the amount of SAM needed for mitigation of a single geologic unit.

Step 1: Summarize the lab testing results and project scope

Table 7.3 SAM Calculation for one rock type

Material ID	Boring Depth (ft)	Excavation Volume (cy)	NP (T/kT)	% Sulfur	Paste pH	Fizz Test
BIF	13.0-15.5	500	0.20	0.07	5.5	n

Step 2: Calculate NNP

$$MPA_{BIF} = (0.07\%\ S)(31.25) = 2.2\ T/kT$$ **Equation 15**

$$NNP_{BIF} = NP_{BIF} - MPA_{BIF} = 0.20\ T/kT - 2.2\ T/kT = -2.0\ T/kT$$ **Equation 16**

(<0; PAG material;

; Table 6.1)

Step 3: Calculate the NPR

$$NPR_{BIF} = NP/MPA = (0.20\ T/kT)/(2.2\ T/kT) = 0.09$$ **Equation 17**

(<1; PAG material;

; Table 6.1)

Step 4: Calculate alkaline addition needed to meet target NNP values

NNP_{Target} = 12 T/kT, excluding a safety factor of 2 (Section 6.7) **Equation 18**

$$NNP_{gap} = NNP_{Targ\text{–}t} - NNP_{BIF} = 12.0\ T/kT - -2.0\ T/kT = 14.0\ T/kT$$ **Equation 19**

Applying the safety factor (2):

$$NNP_{required} = NNP_{gap} \times FS = 14.0\ T/kT \times 2$$ **Equation 20**

= 28 T/kT, or 28 tons of $CaCO_3$ per 1 000 tons of BIF rock

Step 5: Determine the quantity of SAM for the project (evaluates purity of neutralizing source). For this example, assume a CCE of 0.85

SAM required for project mitigation = $NNP_{required}$ x material mass / CCE
= 28 T/kT x (500 cy x 2.2 T/cy x 1 kT/1 000 T) / 0.85
= 36.2 tons SAM

Step 6: Adjust dosing rate based on moisture

Moisture-corrected SAM = (SAM application rate) / (100- % moisture) x 100
= 36.2 tons SAM/(100-12) x 100
= 36.2/88 x 100 **Equation 21**

= 41.1 tons SAM for the 500 CY BIF project

As can be observed, increasing moisture contents in SAM will cause a need for increased SAM dosing rates, since the neutralization rate is based on mass (to which moisture contributes).

EXAMPLE 2 – TWO ROCK TYPES

This example calculates the amount of SAM needed for mitigation for two rock types encountered with weighted-average conditions.

Step 1: Summarize the lab testing results and project scope

Table 7.4 SAM calculation for two rock types

Material ID	Boring Depth (ft)	Excavation Volume (cy)	NP (T/kT)	% Sulfur	Paste pH	Fizz Test
BIF	13.0-15.5	500	0.20	0.07	5.5	n
Dacite	15.5-20.5	1 000	0.1	0.18	4.5	n

Step 2: Calculate NNP

MPA_{BIF} =(0.07% S)(31.25)
= 2.2 T/kT **Equation 22**

MPA_{Dacite} =(0.18% S)(31.25)
= 5.6 T/kT **Equation 23**

$MPA_{Wt\ Avg}$ = [(MPA_{BIF} x $Volume_{BIF}$)+ (MPA_{Dacite} x $Volume_{Dacite}$)] / ($Volume_{BIF}$ + $Volume_{Dacite}$)
= [(2.2 T/kT x 500 cy) + (5.6 T/kT x 1 000 cy)] / (500 cy + 1 000 cy)
= 6 700 T/kT x cy / 1 500 cy
= 4.5 T/kT **Equation 24**

$NP_{Wt\ avg}$ = [(NP_{BIF} x $Volume_{BIF}$)+ (NP_{Dacite} x $Volume_{Dacite}$)] / ($Volume_{BIF}$ + $Volume_{Dacite}$)
= [(0.2 T/kT x 500 cy) + (0.1 T/kT x 1 000 cy)] / (500 cy + 1 000 cy)
= 110 T/kT x cy / 1 500 cy
= 0.07 T/kT **Equation 25**

$NNP_{Wt.\ Avg}$ = $NP_{Wt.\ Avg}$ – $MPA_{Wt.\ Avg}$
= 0.07 T/kT – 4.5 T/kT
= -4.43 T/kT (<0; PAG material
; Table 6.1) **Equation 26**

Step 3: Calculate the NPR

$NPR_{Wt,\ Avg}$ = $NP_{Wt\ Avg.}$ /$MPA_{Wt\ Avg.}$
= (0.07 T/kT) /(4.5 T/kT) = 0.02 (<1; PAG material;
; Table 6.1) **Equation 27**

Step 4: Calculate alkaline addition

NNP_{gap} = (NNP_{Target})- ($NNP_{Wt.\ Avg}$)
= (12.0 T/kT) – (-4.43 T/kT)
= 16.4 T/kT **Equation 28**

Applying the Factor of Safety (2):

$NNP_{required}$ = NNP_{gap} x FS
= 16.4 T/kT x 2 **Equation 29**
= 32.8 T/kT or 33 tons of $CaCO_3$ per 1 000 tons of rock

Step 5: Determine the quantity of SAM for the project mixing (evaluates purity of neutralizing source)

SAM required for project mitigation: = ($NNP_{required}$) x (material mass) / (CCE)
= (33 T/kT) x (1 500 cy x 2.2 T/cy x 1 kT/1 000 T) / **Equation 30**
= 128 tons

Step 6: Adjust dosing rate based on moisture

Moisture-corrected SAM = (SAM application rate) / (100- % moisture) x 100
= 128 tons SAM/(100-12) x 100
= 128/88 x 100 **Equation 31**

= 145 tons SAM for the 1 500 cy combined project volume

EXAMPLE 3 - PROJECT AREA DOSING CALCULATIONS

Calculating neutralization dosing rates for a larger set of borings or outcrops involves calculating the area average, as described in Table 7.5, then using the approach described in the first example for calculating a dosing rate.

Table 7.5 Project Area SAM mitigation needs

Material	Volume represented	NP	AP	% of volume	NP, weighted	AP, weighted
Borehole A	500	2	1.4	9%	0.19	0.13
Borehole B	1000	0.7	12	19%	0.13	2.22
Borehole C	1250	1	8	23%	0.23	1.85
Borehole D	750	20	0.5	14%	2.78	0.07
Borehole E	500	4	1.5	9%	0.37	0.14
Borehole F	600	6	0.8	11%	0.67	0.09
Borehole G	800	2	2	15%	0.30	0.30
Sum:	NA	NA	NA	100	4.66	4.80

NA – not applicable
NP weighted = 4.7
AP weighted = 4.8

This material has an NNP of -0.1, and an NPR of ~0.95, therefore considered PAG material.

7.5 DISPOSAL

For small quantities of PAG, it may be more cost-effective to haul the PAG material to a subtitle D landfill, provided the acceptance criteria for the facility are met. Typical landfilling practices include providing daily cover while the cell is being filled. The leachate collection system of subtitle D landfills are designed to capture any liquid from the combined waste volume for treatment. This would include any potential acid formed from the PAG material.

7.6 APPLIED CONSIDERATIONS FOR CONSTRUCTION

7.6.1 Supplemental Alkaline Material Amendment Material

Several considerations for evaluating, storing, and mixing SAM, as discussed below.

7.6.1.1 Assessing Suitability

Suitability of SAM includes consideration of grain size, CCE, and other potential constituents present within the SAM. Introduction of SAM with too fine of grains may allow for erosion, particularly in uncovered repository settings or open channel settings. A distribution of SAM grain size may be achieved by mixing crushed limestone and agricultural lime. Crushed limestone will often be available from quarries in a Class V distribution, which is comprised of material predominantly gravel and sand-sized grains, and having less than 3% fines (i.e., silt/clay; material passing the #200 sieve). The agricultural lime is often a sand-sized grain (majority of material passing the #60 sieve).

Suitability of SAM also includes evaluation of CCE, which is expressed as a percentage relative to pure calcium carbonate. Pure calcite has a CCE of 100%. Typical values of CCE are shown in Table 7.6.

Table 7.6 Calcium Carbonate Equivalence in Common Supplemental Alkaline Materials

Alkaline Material	CCE (%)
Limestone - $CaCO_3$	100
Industrial byproducts (wastewater sludge, etc.) – composition varies	Varies
Dolomitic Limestone - $CaMgCO_3$	109
Slaked Lime - $Ca(OH)_2$	136

Table source: Pennsylvania State University Extension website

Assessing suitability of SAM should also include consideration of additional constituents which may add to the loading to the environment. An example might be wood pulp sludge, which has neutralizing capacity, but also has elevated chloride and sulfate concentrations. The additional potential for loading of other constituent to the environment needs to be balanced with cost, availability of material, and the potential for deleterious effects.

7.6.1.2 Storage and Handling

Supplemental alkaline material shall be stored on a plastic liner, located within a bermed area (one-foot height) to prevent stormwater runoff and run-on. SAM stockpiles shall be covered daily with plastic and when not in use.

7.6.1.3 Blending

The field approach to blending the SAM and PAG material will vary depending on the dosing rate. For large volumes of SAM addition, the SAM may be added to each dump truck load of PAG material at the rates calculated above. Dumping and bulldozing the material over several dump truck loads will provide significant mixing. If additional mixing efforts are deemed necessary by the QP, mixing may be performed by ripping, bulldozing, or using an excavator to further mix materials. Field observations for visual mixing will be important for determining the degree to which the PAG material and SAM are mixed.

There are practical limitations to achieving an ideal blend using construction scale equipment. For smaller SAM dosing rates, it may be necessary to distribute a layer of SAM over the PAG material after it is dumped. Visual evaluation of mixing will be less effective at smaller dosing rates.

7.6.1.4 Use and Blending of aggregate/borrow/overburden sources

Overburden may be acquired from on-project and off-project sources and blended into a PAG repository, if necessary. Mitigation dosing rates will be evaluated using the same approach as rock mitigation neutralizing rates.

7.6.2 PAG Repository Siting

Siting of the PAG repository will be guided by site design and grade of the roadway, hydrology, width of right-of-way, other available land, and distance from the source area of the PAG material for placement in the repository. The repository location will need to be integrated into the roadway design to allow for MnDOT-allowable grades and turning radii.

7.6.3 Construction Protocols

Selection and preparation of the PAG repository is important both in terms of project cost as well as effectiveness. Site preparation includes implementation of erosion BMPs, preparation of the repository subgrade (e.g., granular import, if needed, leveling of grade, clearing and grubbing, if needed, etc.), and potentially import of granular soils to develop a minimum 5-foot vertical separation of the repository to the pre-construction maximum groundwater elevation. Immediately underlying the PAG material a lower neutralizing layer may be constructed, described in Section 7.4.1.1.

Best management practices related to stormwater management are required for stockpiled neutralization materials. Further, the neutralizing materials shall be covered during precipitation events and at the end of each work day to minimize the amount of exposure to moisture prior to mixing with the PAG material. Similarly, the PAG material in the repository should follow best management practices, including daily covering of piles during precipitation events and the end of each work day.

7.6.4 Blasting and Rock Cut Considerations

On projects where rock excavation is performed, special provisions will be prepared depending on the type of excavation (controlled or production, for instance). The special provisions will consider the following objectives:

1) The resulting rock cut face will be smooth and free of loose fragments and jointing, to the degree possible. Typically, this will entail:
    a. Using pre-split lines to minimize overbreak and ensure a smooth finished surface or shear plane along the specified backslope. The construction contractor should be able to demonstrate their methods and ability to meet the specification by providing a passing blast test section. If excavation drilling or blasting personnel or methods change during the course of the project, a new test section will be required; and
    b. Scaling the exposed faces with construction equipment to ensure that the resulting finished surface or shear plane meet the specified backslope without rock protrusions.
2) The amount of flyrock and debris will be minimized. Typically, this will require:
    a. Removal of all unconsolidated materials from the rock surface prior to blasting;
    b. Use of blast mats or other restrictive materials to prevent flyrock from migrating out of the right-of-way; and
    c. Subsequent cleanup and recovery of PAG materials that are transported off the construction right-of -way.

7.6.5 Construction Phase Sampling

Construction phase sampling may be used to confirm the results of the Monitoring Plan and to inform if greater levels of mitigation are required. All field observation locations shall be recorded by GPS with a 3' accuracy. Sampling frequency during construction, analytes and testing methods will be developed and documented in the Mitigation Plan, based on the QP's professional judgement, the project scope and the results obtained during screening and characterization.

7.6.5.1 Blasthole Boring Observations

Materials generated during project implementation provide an opportunity to verify observations from desktop study, field reconnaissance, and Characterization Program sampling. Field tests or combustion-infrared spectroscopy testing may confirm prior results or inform the project team of unanticipated acid-generating materials (i.e., not anticipated after pre-construction sampling and analysis).

7.6.5.2 Blasthole Sampling

Evaluation and observation of disturbed materials continues through construction. Production drilling for blasting often employs air-rotary drilling. Air-rotary drill methods generate powdery-to-sand-sized cuttings and rock chips. The cuttings may be collected in suitable containers (e.g., 1- or 5-gallon buckets) placed under the cuttings chute near the drill head. Cuttings from the vacuum discharge should not be collected for analysis, as these materials tend to be less correlated with drilling depth than the courser-grained cuttings from the chute.

Borehole locations should be staked or flagged with the horizontal location and the anticipated cut depth. Sampling that is designed to represent the full stratigraphy to be represented in a blast section must also include the anticipated overbreak depth, as material in the overbreak beyond the planned depth will be entrained in the blast volume during expansion of the blast.

For air-rotary sampling, collect all materials returned by the drill. Ensure that the drill rig dust collectors are functioning properly, and are not cross-contaminating samples. Samples from air-rotary drilling must be air-dried prior to containerizing, and sealed in air-tight containers. Under field conditions where wet samples are provided, drying must be accommodated as quickly as possible to avoid initiation of sulfide oxidation prior to testing.

Depth measurements shall be made of the boreholes with a measuring tape or survey staff, to the nearest tenth of foot. GPS locations and digital photographs will be recorded along with general field conditions. The cuttings will be placed into clean and clearly-marked containers for transport to the laboratory with a chain of custody. The containers (e.g., core boxes or 5-gallon buckets, etc.) will be marked with the following information on the body of the container and the lid:

- Project number/name/date
- Borehole number (i.e., Project Station-Position-Cut Depth, e.g., 319+00-12RT-2.6)
- Borehole interval (depth)

Air-rotary samples are typically generated relatively quickly, and sample grain sizes are chips or finer, so the rock description and observations may be limited to:

- An interpretation of the prevalent lithology in the sample
- Identification of visible sulfide mineralogy in matrix materials or in coarse clasts
- Other notable features.

If it is not practical to retain all the material collected from a given interval due to storage limitations, homogenize the material for that increment by using a mechanical splitter, quartering, or using the miniature stockpile method, as described in AASHTO T 248.

All cuttings samples will be collected and stored in appropriate containers and properly labeled to allow for positive identification of the sample date, project, boring number, and depth increment.

7.6.5.3 Imported Materials and Construction Stage Observations

Imported materials may be tested prior to acceptance for use on the project, based on QP recommendations developed and documented in the Mitigation Plan. Imported materials may only be allowed for usage if excavated from above an elevation 10 ft above an identified redox zone at the source area (to be identified by QP). Crushing of imported, unconsolidated materials is discouraged as it is difficult to assess potential for acid generation from coarse-grained materials. However, this may be done at the discretion of the QP. Soil excavations should be observed for unanticipated acid-generating materials (i.e., not anticipated after pre-construction sampling and analysis).

7.6.6 Contractual Language

When using MnDOT staff and equipment, the crews shall be directed to follow the best practices for minimizing blasting dispersion of PAG materials (e.g., blast blankets, test panels) as well as the best practices related to immediate covering of PAG materials when exposed (daily and when not an active working area). When using contractors, these practices should be incorporated into contract requirements, with disincentives for non-compliance or missed timelines, in sufficient dollar amounts to merit contractor consideration and compliance. Quantitative descriptors will help clarify the desired outcomes and financial penalties for non-compliance.

7.6.7 Presence of Utilities

Subsurface utilities should be avoided in the areas of repositories, as subsurface utilities represent potential future disturbances (exposure to moisture and oxygen). Crossings may also introduce a preferred flow pathway for moisture and/or oxygen in cases where pipe bedding material is more granular or less compacted than surrounding materials (native or roadbed).

7.7 TREATMENT

Whether by design, constraint, or observation, some water treatment may be required during or after construction activities. This Guidance Document is not intended to be a design manual for the treatment of ARD. If a site requires water treatment, a water treatment professional (WTP) is needed to evaluate site conditions and design an appropriate treatment system.

7.7.1 Active Treatment

Active treatment refers to modification of water chemistry with *ex situ* or *in situ* methods, typically including reagent addition and mechanical inputs. Often an active system involves tanks, pumps, chemical additives, filters, and associated water treatment methodologies. Significant space is required for active treatment systems, and maintenance over time is required. If active treatment is anticipated for the site, coordination with other MnDOT groups, including right-of-way, is recommended early to guide a comprehensive solution.

Active treatment systems are generally appropriate for severely impacted water, high flow rates, large treatment areas, or other areas where passive treatment is infeasible. Approaches may include neutralization of acidity, precipitation of dissolved constituents, and physical separation of suspended particles.

7.7.2 Passive Treatment

Passive treatment may require less space, energy, chemical/reagent use, and time than active treatment. It is limited to less severe impacts and lower flow rates, but given the linear nature of roadways, relatively long residence time can be achieved with gravity flows, given appropriate topographic conditions. However, care needs to be exercised to avoid introducing water to the PAG consolidation areas by loading the adjacent ditches with surface water for treatment. An example of a situation where passive treatment is a viable approach is when visible sulfide minerals are identified on a rock outcrop poorly suited for isolation mitigation. In this case, the surface water drainage ditch along the base of the cut should be lined with approved gravel to cobble-sized alkaline material.

Passive treatment also may include limestone-lined settling ponds, subsurface limestone drains to achieve anoxic conditions, and wetland construction to create anoxic/reducing conditions.

Passive systems require upkeep, maintenance, and documentation. Typical maintenance includes routine items such as repair from storm events. Other upkeep to preserve or restore functionality may include replacement of limestone if the material is armored with precipitates, or replacement of some of the material due to preferential erosion or other disruption.

7.8 MITIGATION PHASES

Based on the decision-making criteria described in Figures 4.1, 4.2, and 4.3, a variety of project scenarios may result in mitigation and/or treatment. In some cases, preemptive mitigation may be appropriate for small volume and low sulfur projects. Larger-scale projects applying previously-described mitigation methods will be monitored for effectiveness (Chapter 8). If the desired project outcomes are not initially achieved, supplemental mitigation or treatment of discharges may be required.

7.8.1 Preemptive Mitigation

Preemptive mitigation refers to a conservatively-neutralized, small-volume mitigation that contains less than the defined threshold sulfur concentration (defined as a *de minimis* condition). The general approach is to mix PAG material and SAM at a 10 parts PAG material to 1 part neutralizing material ratio (10:1). Calculations and assumptions used to support the use of this mixing ratio are included in Appendix F.

Documentation supporting this approach should be developed and added the project records. Due to the small project areas, pre-construction and post-construction monitoring is not included for preemptive mitigation implementations.

7.8.2 Mitigation Plan

If mitigation or treatment is determined to be appropriate, the QP shall develop a Mitigation Plan that uses the screening and characterization sampling results to inform the mitigation and treatment approaches, dosing rates, field methods (as appropriate), and desired project outcomes. Monitoring is required for all mitigation projects, unless considered *de minimis*, as described in the Monitoring Plan described in Chapter 8.

7.8.3 Supplemental Mitigation

If monitoring for mitigation projects indicates that the results are higher than anticipated, or exceed the project-specific goals as identified by the QP in the Mitigation Plan, supplemental mitigation or effluent/runoff treatment may be required. This should be determined in consultation with the property owner and regulatory agency, as needed.

CHAPTER 8: PRE AND POST MITIGATION CONSTRUCTION MONITORING

Monitoring is the process of routinely, systematically, and purposefully gathering information for use in decision making. Monitoring characterizes environmental changes from construction activities to assess conditions on the site and possible impacts to receptors (INAP, 2014). Projects requiring construction mitigation also generally require water quality monitoring to assess both the baseline (background) conditions as well as the efficacy of mitigation efforts.

The purpose of this chapter is to outline pre- and post-mitigation and construction monitoring activities that may be implemented to document the effectiveness of PAG material mitigation measures as well as the overall impact the construction project may have on the project area related to PAG material. If mitigation is deemed necessary following the completion of the Characterization Program, the next step is to develop a Mitigation Plan (Chapter 7). As part of the Mitigation Plan, a Monitoring Plan will be developed prior to beginning construction to outline the sampling requirements specific to the project area. The footprint of the PAG site should also be added to the MnDOT Geotechnical Asset Management layer of Georilla. A Receptor Survey should also be conducted as part of the Monitoring Plan.

Following the development of the Monitoring Plan, the monitoring network should be installed and pre-construction monitoring (baseline monitoring) should begin with the results summarized in a Baseline Sampling Report. Once construction begins and mitigation is implemented, Annual Monitoring Reports will be compiled until completion of the monitoring period. If impacts are observed following mitigation, a Supplemental Mitigation Plan and/or Extended Monitoring Plan may be warranted. Upon completion of monitoring, a Final Post Construction Monitoring Report should be completed, depending on pertinent permitting requirements. Details of these activities are discussed in the following sections.

8.1 MONITORING ACTIVITIES

Surface and groundwater monitoring as well as physical inspections of PAG fill areas will be conducted prior to, during, and after mitigation and construction activities. The specifics of these activities will be detailed in the project Monitoring Plan. This section will describe the monitoring objectives and requirements of each of the phases of monitoring.

8.1.1 Baseline Monitoring

For projects where PAG materials will likely be encountered during construction and mitigation, and post-construction monitoring is deemed necessary, it is imperative to understand the baseline surface water and groundwater properties prior to and through the duration of construction. This information is critical to interpreting water quality data collected during and after project construction and assessing effectiveness of mitigation. The purpose of baseline sampling is to develop an understanding of surface water drainage and groundwater flow direction and quality, developed from information collected as part of the desktop study, field reconnaissance, Characterization Program, and Receptor Survey.

Baseline water quality should commence at least one year prior to soil and/or rock disturbance, collecting at least one sample per quarter.

8.1.2 Post-Construction Monitoring

Post-construction monitoring in the project area should be completed for five years following construction depending on the project conditions (INAP, 2014) to verify that the mitigation measures are functioning as intended. The multi-year time period for post-construction monitoring is necessary to ensure that the weathering process for the excavated rock has time to develop and produce conditions that will be representative of the final project status. If impacts are observed, extended monitoring will be required.

8.1.3 PAG Repository Monitoring

PAG repositories represent areas for long-term storage of PAG materials. These areas should be visually inspected and photographed to document changes over time and identify any structural instability or water quality impacts from mitigation measures (MEND, 1990). Inspection will take place twice per year in conjunction with surface and groundwater monitoring for signs of:

- Erosion and settling (slumping, rills, and gullies);
- ARD seepage (iron staining, salt formation, and biomass accumulation);
- Stressed vegetation (wilting/yellowing/dying leaves and stunted growth); and
- Other anomalous conditions.

Conditions of the fill areas should be thoroughly assessed, particularly in those areas that are directly hydraulically downgradient.

8.1.4 Extended Monitoring

If post-construction monitoring or PAG management area monitoring results indicate that the project has had an adverse impact on the construction site area, extended monitoring may be required. An adverse impact maybe defined as an increase in the parameters being monitored (metals, pH etc.) or a physical change noted near any PAG management areas (stressed vegetation, staining, etc.). In these cases, the Mitigation Plan and Monitoring Plan will be reevaluated in consultation with MnDOT and applicable regulatory agencies. Potential outcomes may be an extended monitoring program or additional mitigation measures, developed by a QP or WTP.

8.2 SAMPLING AND ANALYSIS PLAN

Since the objective of the monitoring program is to evaluate the project's effect on the environment, monitoring should occur at all stages of the project from preconstruction until final closure (INAP, 2014). Since there may be differences depending on the project area, material handled and type of the construction activities, the Monitoring Plan will contain the site-specific approach and procedures to be used during the monitoring. The project elements used to gather the information for the Monitoring Plan include the project Construction Plan and will include a site-specific Receptor Survey.

8.2.1 Monitoring Plan Development

To develop the Monitoring Plan, the Construction Plan for the project should provide information on the project activities, whereas the site-specific Receptor Survey will evaluate the areas that may be potentially impacted. Overall, for Monitoring Plan development the Construction Plan for the project will provide:

- Location and magnitude of the surface and subsurface disturbance; and
- Location of any disposal areas

A Receptor Survey will be completed to provide additional information for the Monitoring Plan. The receptor survey will include:

- An evaluation of waste disposal drainage discharge locations (e.g. seeps, drainage);
- Groundwater gradient evaluation;
- Local surface water bodies;
- Drinking water well locations; and
- Locations of any sensitive species/biological features within the project area

In addition to the Construction Plan and Receptor Survey, the design of Monitoring Plan will consider the following for each project (MEND, 1990):

- Magnitude of the project (is it *de minimis*?);
- Preliminary study of variances and seasonal patterns;
- Interactive planning to clarify monitoring objectives; and
- Process for periodic review

As a result of this design, the final project-specific Monitoring Plan, at a minimum, must include:

- Sampling and analytical procedures;
- Analytical parameters;
- Inspection procedures;
- Frequency of monitoring;
- Monitoring locations;
- Statistical analysis methodology; and
- Reporting requirements.

For any project, the items that should be considered for a monitoring program include surface water, groundwater, and PAG management or fill areas. *De minimis* projects may require less sample collection and only management area performance monitoring depending on the project.

8.2.2 Surface Water Monitoring

If surface water is present near or adjacent to the project area, it must be included in the Monitoring Plan. Sample locations will include natural water bodies (streams, lakes, etc.) adjacent, hydraulically downgradient, and/or susceptible to rainwater runoff from any PAG rock fill areas. At a minimum, the parameters to monitor in surface water are included in Table **8.1** at the frequency described in Table 8.2 and must be outlined in the Monitoring Plan.

Table 8.1 Sample Parameters and Suggested Analytical Methods

Parameter	Analytical Method
General Chemistry Parameters	**General Chemistry Analytical Method**
Field measurements - pH, temperature, oxidation reduction potential (ORP), electrical conductivity , turbidity	field-portable multi-parameter sonde or equivalent
Alkalinity, Total	Standard Methods 2320 (American Public Health Association, American Water Works Association, and Water Environment Federation)
pH (laboratory) – if not collected in the field	Standard Methods 4500-H^+ (American Public Health Association, American Water Works Association, and Water Environment Federation)
Sulfate	USEPA 300.0
Chloride	USEPA 300.0
Nitrate	USEPA 300.0
Total suspended solids	Standard Methods 2540 D (American Public Health Association, American Water Works Association, and Water Environment Federation)
Total dissolved solids	Standard Methods 2540 C (American Public Health Association, American Water Works Association, and Water Environment Federation)
Total and Dissolved Metals	**Metals Analytical Methods**
Calcium	USEPA 200.7 – these metals are more abundant in nature and this analytical method contains adequate detection limits to characterize them
Magnesium	USEPA 200.7 – these metals are more abundant in nature and this analytical method contains adequate detection limits to characterize them
Potassium	USEPA 200.7 – these metals are more abundant in nature and this analytical method contains adequate detection limits to characterize them
Sodium	USEPA 200.7 – these metals are more abundant in nature and this analytical method contains adequate detection limits to characterize them

Parameter	Analytical Method
Arsenic	USEPA 200.8 – these metals tend to be less abundant in nature and are often bound within sulfide minerals; this analytical method has adequate detection limits to characterize them.
Copper	USEPA 200.8 – these metals tend to be less abundant in nature and are often bound within sulfide minerals; this analytical method has adequate detection limits to characterize them.
Nickel	USEPA 200.8 – these metals tend to be less abundant in nature and are often bound within sulfide minerals; this analytical method has adequate detection limits to characterize them.
Antimony	USEPA 200.8 – these metals tend to be less abundant in nature and are often bound within sulfide minerals; this analytical method has adequate detection limits to characterize them.
Selenium	USEPA 200.8 – these metals tend to be less abundant in nature and are often bound within sulfide minerals; this analytical method has adequate detection limits to characterize them.
Zinc	USEPA 200.8 – these metals tend to be less abundant in nature and are often bound within sulfide minerals; this analytical method has adequate detection limits to characterize them.

8.2.3 Groundwater Monitoring

Groundwater is a common source of drinking water in northern Minnesota; tens of thousands of wells intersecting surficial and fractured bedrock groundwater resources provide drinking water to homes, cabins, municipalities, schools, and businesses. If groundwater may be impacted at the construction area, monitoring wells should be installed at locations hydraulically up- and down-gradient of the constructed alignment and PAG rock fill areas. The monitoring network must be designed by a QP, and care should be used to design the network to represent conditions after completion of the project rather than be representative of existing conditions (INAP, 2014).

An assessment of local drinking water wells will be conducted within ½ mile of the project area or within an acceptable proximity, as informed by the surface and groundwater flow directions. A query of the MDH CWI will be performed to compile a list of local wells. Water samples will be collected during monitoring programs for the parameters listed in Table 8.1 at the frequency shown on Table 8.2 as detailed in the Monitoring Plan.

Prior to any monitoring well installation, the seasonal variability of the water table should be considered. It is recommended that a minimum of two monitoring wells be installed (nested) and surveyed at each location – one intersecting the water table and one deeper to measure the potential vertical hydraulic gradient. Consideration shall be given for installing wells near fault zones, which may act as conduits for groundwater flow (MEND, 1990). The procedures for each sampling event must include:

- Water level measurements (to the nearest 0.01 foot);
- Well stabilization (ASTM D6452-99);
- Sample collection (per a project-specific Monitoring Plan); and

- Event documentation (ASTM D6089-15).

Monitoring well stabilization parameters to be documented include pH, temperature, turbidity, and specific conductance. Oxidation-reduction potential and dissolved oxygen data should be recorded for evaluation but will not be used to demonstrate stabilization. Purged water may be discharged onto the ground, unless obvious evidence of impacts is observed or previous water quality results indicate the presence of potential chemicals of concern.

Groundwater will be sampled following the industry standard collection practices that will be detailed in Standard Operating Procedures (SOPs), included in the project Monitoring Plan. Sample parameters and suggested analytical methods are the same as those for surface water, included in Table **8**.**1**.

8.2.4 Monitoring Frequency

The frequency of the monitoring for each of these areas may be dependent on the project, and specifics should be included in the Monitoring Plan; however, monitoring should be frequent enough to identify potential issues as soon as possible to allow for additional mitigation to minimize any long-term impacts to a project area (INAP, 2014). Suggested frequencies are included on Table 8.2.

Table 8.2 Suggested Site Monitoring Frequency and Duration

Activity	Monitoring Frequency	Monitoring Duration Period
Pre-Construction (Baseline)	Baseline Frequency	Baseline Duration
Surface water sampling	Bi-annually (spring, fall)	1 year
Groundwater sampling	Quarterly	1 year
Post-Construction	Post-Construction Frequency	Post-Construction Duration
Surface water sampling	Bi-annually (spring, fall)	5 years
Groundwater sampling	Quarterly or 3x/year	5 years
Structural/erosional inspections	Bi-annually (spring, fall)	5 years
Site observations/photographs	Quarterly or 3/x year	5 years

8.3 REPORTING

After completion of each phase of the monitoring activities, reporting will be completed and sent to MnDOT. The potential reports required for each project include, the Baseline Monitoring Report, Annual Post-Construction Monitoring Report, and the Final Closure Monitoring Report.

8.3.1 Baseline Monitoring Report

This report is completed at the completion of the baseline monitoring period and will include the results from the sample collection efforts. Reporting includes:

- The dates of all activities (sampling events, etc.) and personnel present for these events;
- A tabulation of all analytical data;

- A map of the project area showing all monitoring well, surface water, and potential PAG fill locations;
- Groundwater elevation maps and hydrographs. These figures will be used to show groundwater flow directions, any seasonal variations, and any changes over time;
- A comparison of groundwater and surface water results to applicable State water quality standards and initial background samples. This comparison will demonstrate natural water quality conditions in relation to State standards prior to construction;
- Statistical analysis of the analytical data. This analysis will demonstrate the water quality over time prior to construction. The statistical analyses may include trend analysis or other limit comparison analyses that demonstrate variability in project water quality; and
- Any suggested changes to the Monitoring Plan.

8.3.2 Annual Post-Construction Monitoring Report

The results from the post-construction monitoring sample collection and physical inspections will be examined annually and reported to MnDOT. Reporting includes:

- The dates of all activities (sampling events, inspections, etc.) and personnel present for these events;
- A tabulation of all analytical data;
- A map of the project area showing all monitoring well, surface water, and PAG fill locations. If project area photographs were collected as part of the site observations, the locations of these should be noted on the map as well;
- Groundwater elevation maps and hydrographs. These figures will be used to show groundwater flow directions, any seasonal variations, and any changes over time;
- A comparison of groundwater and surface water results to applicable State water quality standards and initial background samples. This comparison should show any immediate impact on State water quality and indicate if the project was the potential cause of any impact relative to natural conditions;
- Statistical analysis of the analytical data. This analysis will help gauge whether the project is having an impact on the water quality over time and allow for additional mitigation measures to be considered before an actual impact. The statistical analyses may include trend analysis or other limit comparison analyses that demonstrate changes in water quality results;
- A description of any physical issues noted during the sampling and inspection of the project and PAG fill areas. This analysis would point to any potential issues with the mitigation activities and allow for correction prior to any potential impacts to the project area. The descriptions should include any additional operation and maintenance activities that were undertaken throughout the year; and
- Any proposed changes to the Monitoring Plan or post-construction monitoring.

Following the monitoring period, the project should be revaluated to determine if monitoring activities can be discontinued, or if additional monitoring or operation and maintenance activities are warranted (INAP, 2014).

8.4 FINAL POST-CONSTRUCTION MONITORING REPORT AND CLOSURE

When the post-construction monitoring period is complete, and extended monitoring is determined to not be warranted, a Final Post-Construction Monitoring Report will be completed. The results from the final post-construction monitoring period will be summarized and reported to MnDOT. Reporting includes:

- An overall summary of the project activities;
- The results of the final statistical analysis of the data;
- A final map of the project area showing all monitoring well, surface water, and PAG fill locations;
- A final groundwater elevation maps and hydrographs;
- A final description and analysis of the status of the PAG fill areas. This analysis would point to any potential long-term issues with the PAG fill areas and any potential institutional control measures (e.g., add to the Geotechnical Asset Management System) to be taken; and
- A rationale for closure of the project monitoring.

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APPENDIX A
NRRI – DIGITAL MAP REPORT

NRRI Technical Report — June 2018

MnDOT Potentially Acid Generating (PAG) Rock Implementation Project: Report on the Digital Map

Submitted by:
Dean M. Peterson

Date: June 27, 2018

Report Number:
NRRI/TR-2018/14

Collaborators:
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Minnesota Department of Transportation

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Natural Resources Research Institute
University of Minnesota Duluth
Driven to Discover

Duluth Laboratories & Administration
5013 Miller Trunk Highway
Duluth, Minnesota 55811

Coleraine Laboratories
One Gayley Avenue
P.O. Box 188
Coleraine, Minnesota 55722

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Natural Resources Research Institute
University of Minnesota, Duluth
5013 Miller Trunk Highway
Duluth, MN 55811-1442
Telephone: 218-788-2682

Email: dmpeters@d.umn.edu

Web site: http://www.nrri.umn.edu

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Environmental concerns exist surrounding the exposure of potentially acid generating (PAG) minerals to water and air and the subsequent aqueous products of their chemical weathering on the Earth's surface. Such concerns have the ability to impact completion of infrastructure projects such as road building. A guidance manual, specifically written for the Minnesota Department of Transportation (MnDOT) and based on a detailed understanding of the geology of Minnesota, would help direct informed project task planning when PAG rock is anticipated to be encountered on a highway project.

To complete a guidance manual, MnDOT must identify the geologic environments and/or formations where PAG rock may be encountered within future MnDOT right of ways. This Natural Resources Research Institute (NRRI) technical report describes the method and outcome of a new geology-based digital derivative map that combines geospatial information and produces a series of rankings on the likelihood of encountering PAG minerals throughout MnDOT Districts #1 and #2 (Fig. 1). The final map has four underlying ranked (from 0-low to 5-high) PAG components: bedrock geology, mineral occurrences, lithologic boundaries, and depth to bedrock that have been intersected and combined digitally using the Geographic Information System (GIS) ArcGIS.

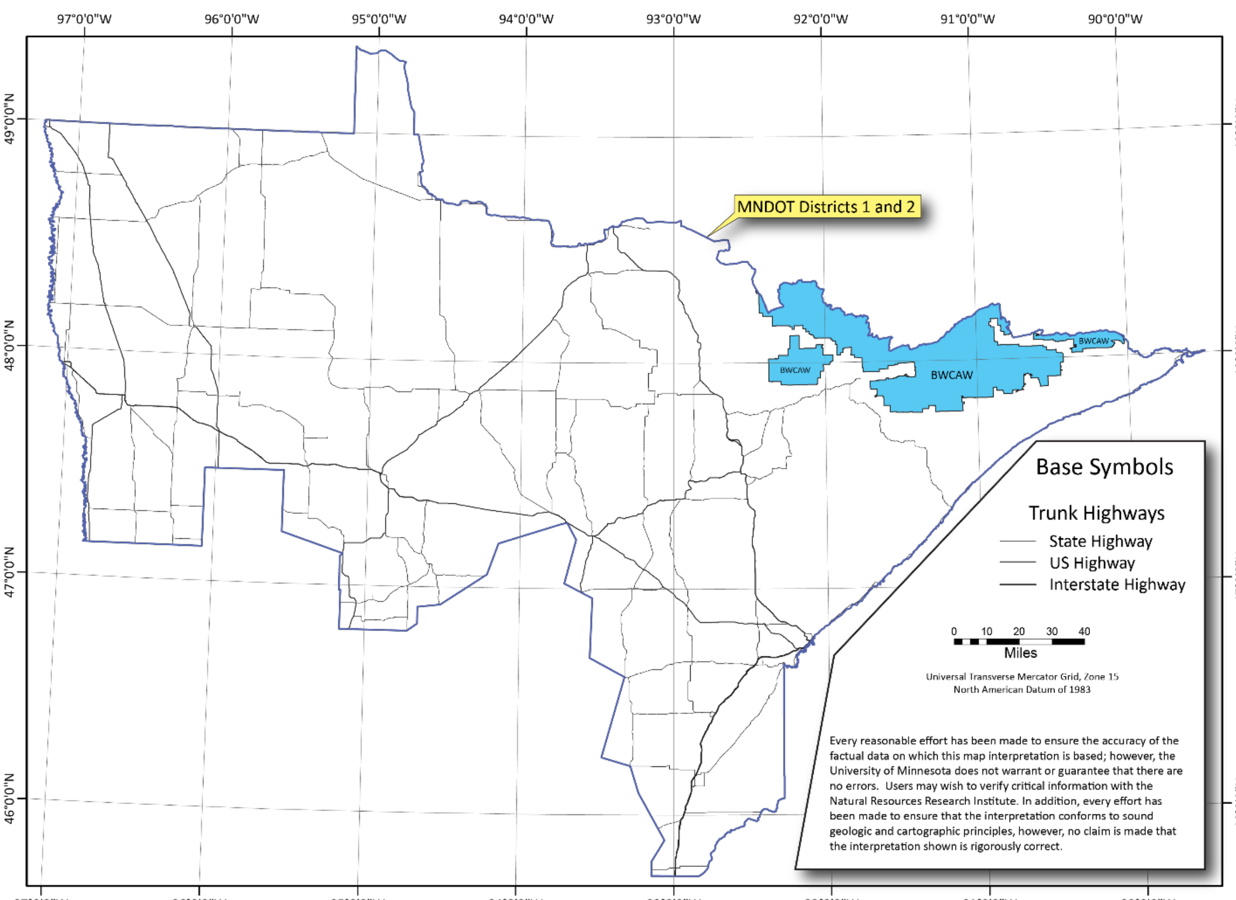


Figure 1. Location map of the study area including trunk highways and the boundary of MnDOT's Districts 1 and 2.

DATA LAYERS

The foundation of the PAG map is composed of three existing detailed digital GIS datasets of the NRRI's Economic Geology Group (Bedrock Geology (1), Mineral Occurrences (2), and Lithologic Boundaries (3)) as well as a newly generated and project-specific Depth-to-Bedrock map (4). The utility of each of these GIS layers for spatial analysis is a result of their understandable and functional attribute tables, which have been modified by the addition of PAG ranking for each feature. Entities within each of the four datasets are ranked from 0 (no known PAG) to 5 (high PAG) in the individual attribute tables. The PAG rankings for each entity in the datasets (Table 1) are based on the authors 30 years of experience studying the bedrock geology and geochemistry of northern Minnesota. The PAG rankings have been vetted by the project's Technical Advisory Panel (TAP).

Table 1. PAG rankings of digital geological entities utilized in this study.

	DESCRIPTION	RANK
Neoarchean Bedrock Units	Volcanic rocks	2
	Clastic sedimentary rocks	1
	Chemical sedimentary rocks	4
	Mafic intrusions	2
	Granitoid intrusions	1
	Felsic porphyries	3
	Migmatitic rocks	0
	Sheared rocks	4
	Graphitic rocks	5
	Sulfide-rich rocks	5
Paleoproterozoic Bedrock Units	Volcanic rocks	2
	Clastic sedimentary rocks	1
	Chemical sedimentary rocks	2
	Chemical sedimentary rocks	4
	Mafic intrusions	2
	Granitoid intrusions	1
	Sheared rocks	4
	Graphitic rocks	5
	Sulfide-rich rocks	5
Mesoproterozoic Bedrock Units	Volcanic rocks	0
	Clastic sedimentary rocks	0
	Troctolitic intrusions	1
	Gabbroic Intrusions	1
	Anorthositic Intrusions	0
	Granitoid intrusions	0
	Sulfide-rich rocks	5

	DESCRIPTION	RANK
Mineral Occurrence	Fe-Sulfide dominant	5
	Cu-Sulfide dominant	4
	Hydrothermal Alteration	3
	Veining	3
	Everywhere else	0

	DESCRIPTION	RANK
Lithologic Boundaries	Shear Zone: Primary	3
	Shear Zone: Secondary	5
	Shear Zone: Tertiary	4
	Fault Zone	3
	Contact: Intrusive	2
	Contact: Sheared	2
	Everywhere else	0

	DESCRIPTION	RANK
Depth to Bedrock	Within 100 meters of outcrop	5
	< 50 Feet	4
	> 50 Feet	0

The GIS combination and spatial analysis of these four separate datasets is schematically presented in Figure 2, and brief descriptions of each of the datasets are presented in the following sections of this report.

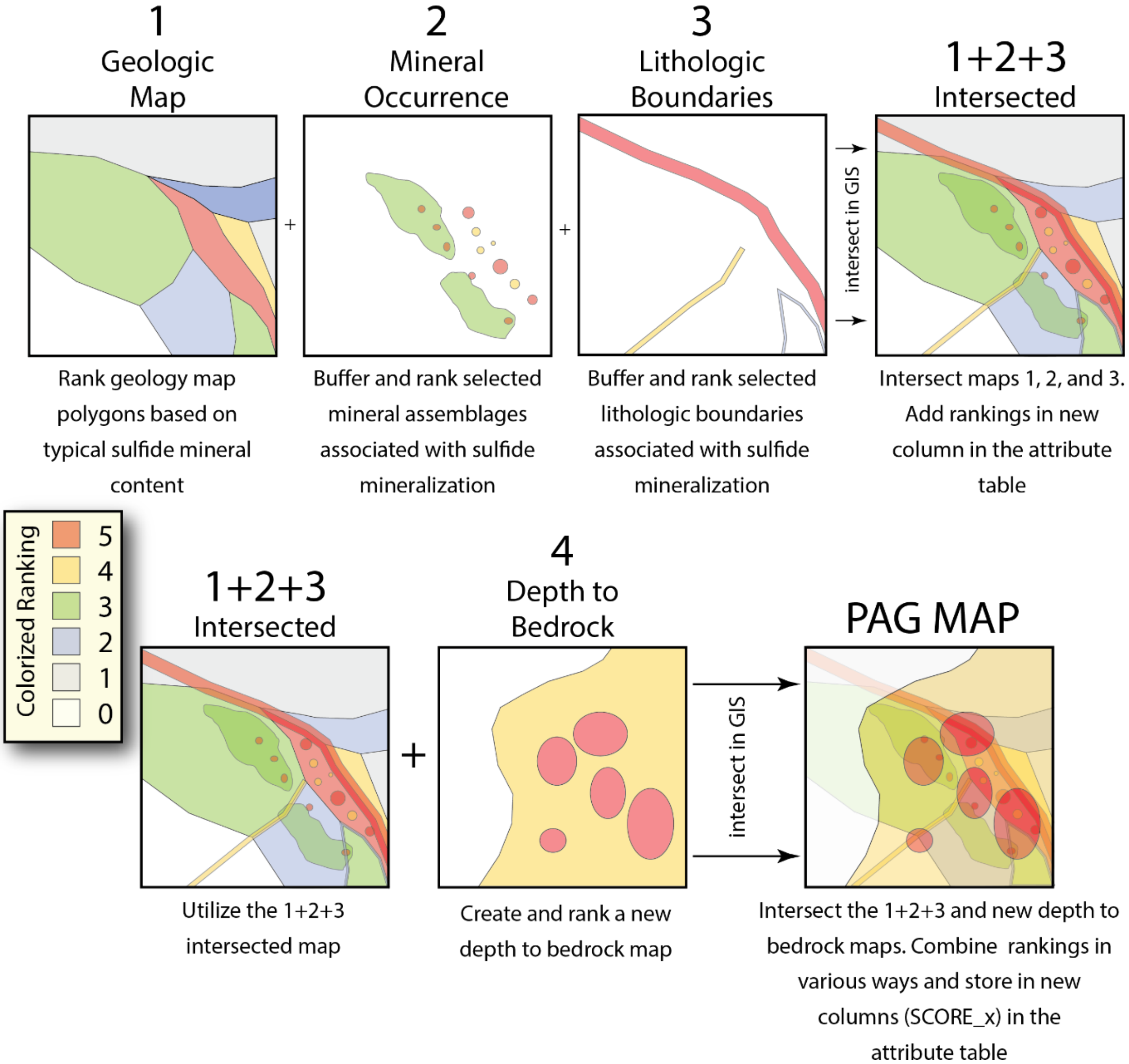


Figure 2. Schematic diagram of the GIS spatial analysis steps utilized to create the final PAG map.

Bedrock Geology

The Precambrian bedrock geology of the study area, MnDOT's Districts 1 and 2, consists of sequences of rocks from three distinct geologic eras (Fig. 3). The oldest rocks are Neoarchean (~16.46 million acres) granite-greenstone belt crystalline rocks of the Canadian Shield. Unconformably overlying these rocks are Paleoproterozoic (~2.92 million acres) supracrustal metasedimentary rocks of the Animikie Basin. The last Precambrian sequence includes Mesoproterozoic (~3.85 million acres) lava flows, mafic to felsic intrusions, and sandstones of the Mid Continent Rift. Sporadically overlying the Precambrian rocks, and generally beneath a thick veneer (>50 feet) of Pleistocene glacial sediments, are flat-lying Phanerozoic sedimentary rocks of the Cambrian, Ordovician, Jurassic, and Cretaceous eras (Fig. 3). In addition, an extensive saprolite residuum of weathered Precambrian bedrock occurs throughout the western portion of the study area.

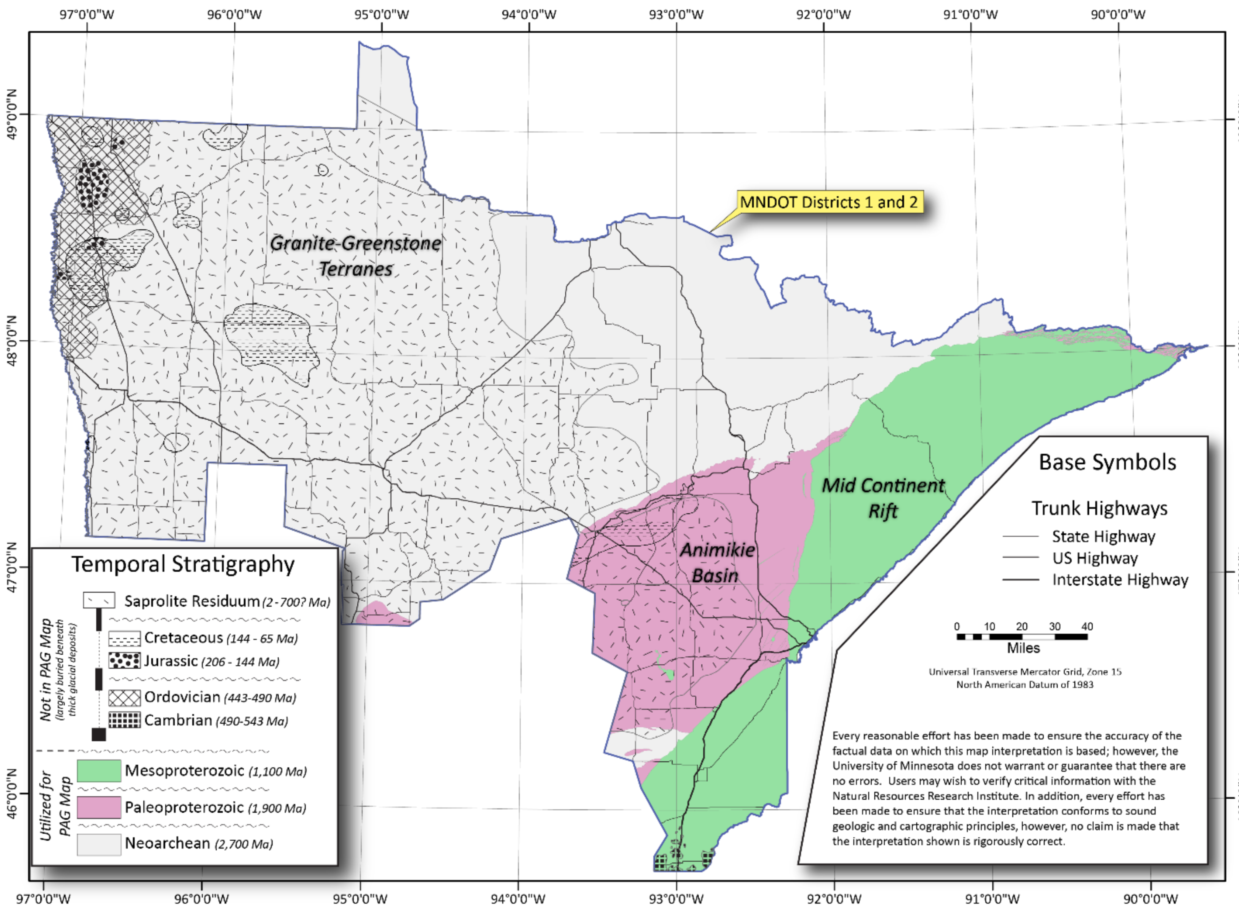


Figure 3. Simplified geologic terrane map of the study area.

The geological data utilized for this project were taken from the NRRI's exhaustive digital compilation of bedrock geologic data for the whole State of Minnesota (Fig. 4). This internal NRRI dataset includes bedrock geology, geologic lines, outcrops, structural symbols, drill holes, geochemistry, gravity and magnetic maps, airborne EM anomalies, mineral occurrences, open pit and underground iron mines, quarries, gravel pits, mineral prospects, exploration test pits and trenches, mineral resources, and mineral potential models. One of the key aspects of this compilation is that each and every entity in the datasets has embedded in the attribute tables the original SOURCE of the information. Therefore, the user of these data can review and vet all of the changes that have been made by the NRRI to seamlessly stitch together this detailed bedrock geologic interpretation.

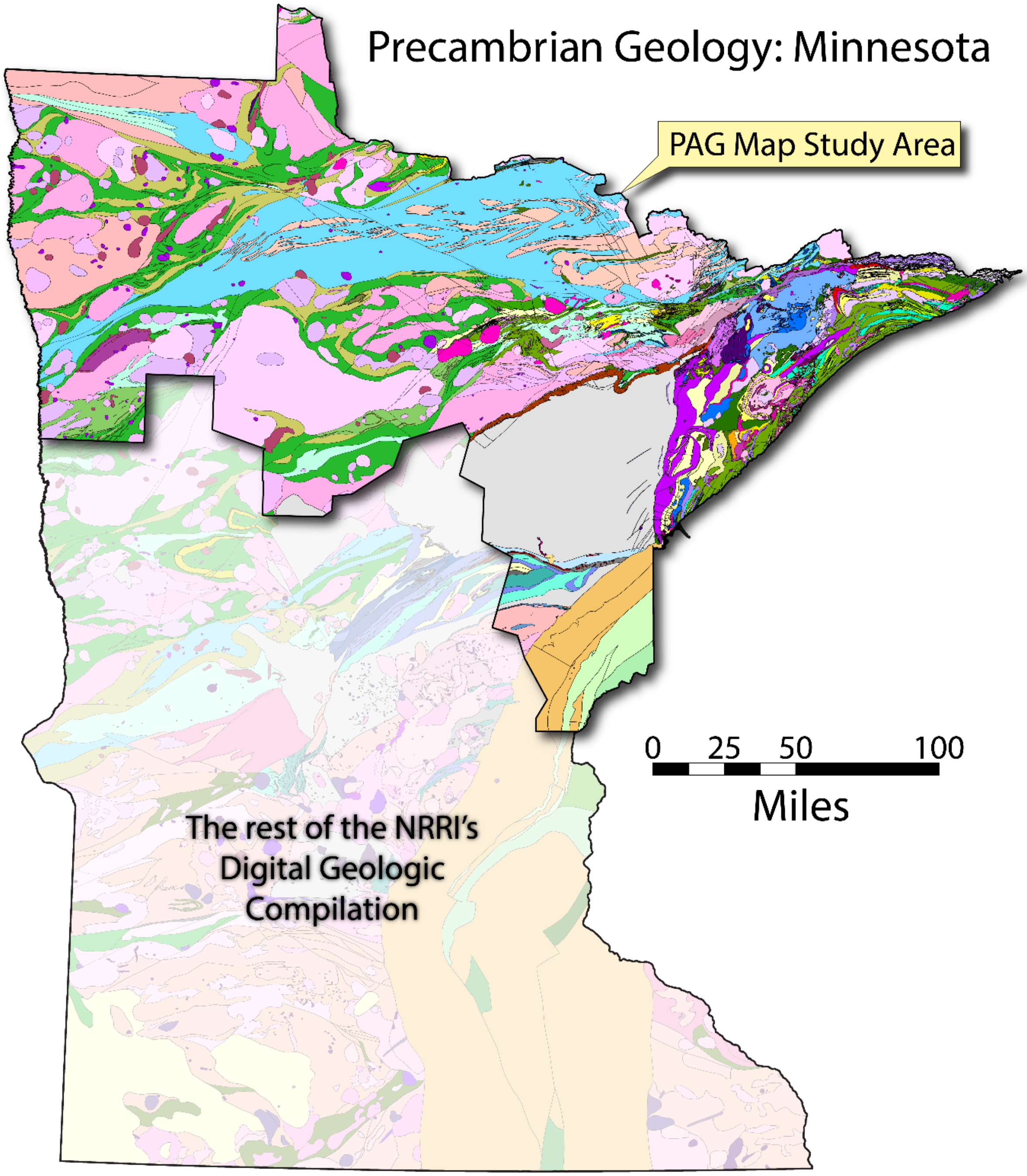


Figure 4. Map of the digital geological clipped from the NRRI's statewide database for use in this study.

The original sources of the NRRI's bedrock geology map data utilized for this project are listed in Table 2. A map of the final clipped bedrock geology and lithologic boundaries of MnDOT's Districts 1 and 2 is presented in Figure 5, with the colorized geologic unit legend in Figure 6. A map depicting the PAG Rank value (which has been added to the attribute table for each polygon of the bedrock geology map based on Table 1/Figure 6) of the Precambrian bedrock geology for the study area is given in Figure 7.

Table 2. Sources used in the NRRI's digital compilation of the Precambrian bedrock geology of Minnesota within the study area. Polys (GIS polygons) and acres listed are those from within MnDOT's Districts 1 and 2 and within the final PAG map generated for this study.

GEO_SOURCE	POLYS	ACRES	GEO_SOURCE	POLYS	ACRES
MGS Map S-22	27,327	13,738,878.1	PRC Capstone, Forest Center 2012	519	9,881.9
MGS Map M-080	1,092	5,194,458.4	DNR 61-25-16, File #1, Item #1	1,713	9,785.8
MGS Map M-119	6,877	1,116,368.4	PRC; Homer Lake Capstone, 2007	372	9,410.1
MGS Map M-068	3,208	413,534.3	MGS Map M-162	197	8,436.3
MGS Map M-075	1,818	185,415.3	MGS Map M-079	315	8,430.5
Dean Peterson: Duluth Metals Ltd.	7,265	162,573.1	MGS Map M-183	967	7,427.6
MGS Map M-002	5,887	128,449.7	MGS Map M-066	1,512	7,005.0
MGS Map M-028	2,054	103,033.2	Talon Metals Corp Presentation Map	24	6,989.6
MGS Map M-081	2,265	101,682.8	MGS Map M-182	484	6,732.5
USGS Map I-2358-B, Sheet 1 of 2	84	97,122.2	MGS Map M-172	928	6,665.4
MGS Map M-197	1,024	94,157.2	NRRI/TR-2003/29	1,348	6,641.9
MGS Map M-174	1,418	91,606.0	PRC/MAP-2014-3	323	6,529.3
MGS Bulletin 39	1,279	84,496.1	MGS Map M-067	22	6,501.0
Peterson, D.M., PhD Study	4,215	75,976.3	MGS Map M-036	1,029	6,378.8
MGS Map M-031	893	69,627.0	PRC/Map-2011-3; Central BWCAW	283	6,127.0
MGS Bulletin 24	4,172	64,719.5	MGS Map M-100	12	5,872.7
MGS Map M-050	3,390	61,835.9	MGS Map M-160	1,115	5,653.4
MGS Map M-072	2,974	60,739.9	PRC Capstone Kekekabic Lake 2015	287	5,553.6
MSG OFR 2010-04	845	60,666.5	MGS Map M-110	346	5,156.0
MGS Map M-082	2,783	51,562.5	MGS Map M-026	629	4,710.7
MGS Map M-181	1,422	48,108.1	PRC Capstone Disappontment Lake 2009	144	4,631.0
MGS Map M-008	1,091	47,789.2	MGS Map M-125	431	4,174.4
USGS Map GQ-1457	1,304	46,283.3	PRC; SKI Capstone, 2014	374	3,858.5
PRC Capstone Ima Lake 2008	808	43,587.8	USGS OFR 85-0246	292	3,844.6
MGS Map M-038	3,170	42,841.3	MGS Map M-176	92	3,738.9
MGS OFR 2016-04	1,168	38,640.8	MGS Map M-064	243	3,212.2
MGS Map M-139	514	37,852.5	NRRI Atlas Project, 2017	61	3,203.1
MGS Map M-065	3,027	35,868.2	MGS Map M-029	233	2,860.8
MGS Map M-189	798	35,129.9	MGS Map M-114	543	2,526.8
MGS Map M-147	735	33,546.0	MGS Map M-046	225	2,517.0
MGS Map M-128	729	32,905.3	PRC, Lake Two Capstone 2012	169	2,513.9
Peterson Geoscience LLC	642	27,868.9	PRC, Lake Three Capstone	145	2,128.1
MGS Map M-007	653	26,871.6	MGS Map M-105	254	1,573.9
MGS Map M-091	1,948	26,382.1	Costello Thesis, UMD 2010	122	1,566.8
MGS Map M-129	230	25,259.5	PRC, Gabbro Lake Capstone 2007	281	1,140.6
MGS OFR 13-01	1,100	25,144.5	Bear Creek Mining, 1969	285	845.6
MGS Map M-161	1,586	24,874.3	MGS Map M-033	34	816.4
MGS Map M-171	634	23,987.6	MGS Guidebook 21	30	731.3
MGS Map M-155	557	23,891.8	MGS Map M-086	262	726.8
USGS Map GQ-1540	1,184	22,325.8	MGS Map M-034	89	722.6
USGS Map I-1527	869	21,872.1	PRC, Lake Vermilion State Park Capstones	185	646.5
MGS Map M-042	1,214	21,654.8	Gruner et al., 1941	4	572.7
MGS Map M-032	550	19,734.7	MGS Map M-165	14	553.0
NRRI Map 2004/01	3,469	19,238.7	MGS Map M-074	33	440.4
MGS Map M-170	331	18,899.9	MGS Map M-030	51	340.9
MGS Map M-195	768	18,696.3	Precambrian Research Center	26	236.0
MGS Map M-140	520	18,602.7	PRC, Twin Lakes Capstone	109	234.4
MGS Map M-039	1,574	18,455.9	Yeomans map for Goldfields (DNR)	116	231.4
MGS Map M-190	409	18,357.7	MGS Map M-059	23	207.2
MGS Map M-159	1,431	18,021.3	PRC, Jack & Weird Lake Capstone	34	153.1
PRC; Crocodile Lake Capstone, 2015	1,165	14,825.5	Newmont Exploration Ltd., 1989	105	128.1
Peterson, D.M., 2015, Hwy 169 Report	3,199	14,820.5	DNR 71-23-36, File #1, Item #3	101	123.5
USGS Map GQ-1527	1,066	13,836.2	PRC, Soudan State Park Project	71	117.5
MSG Map M-027	568	13,341.5	USGQ Map I-2358_B	7	79.9
PRC; Temperance Lake Capstone, 2014	445	11,801.5	PRC; Cherokee Lake Capstone, 2015	7	43.3
MGS Map M-179	414	11,391.5	DNR Report 326	35	39.1
USGS Map GQ-1423	1,448	11,190.8	MGS Map M-017	5	14.8
MGS Map M-198	642	11,132.2	PRC; Purvis Road Project	23	14.4
PRC, Sawbill Lake Area capstone	226	10,625.4	**Grand**	**142,161**	**23,224,657.9**

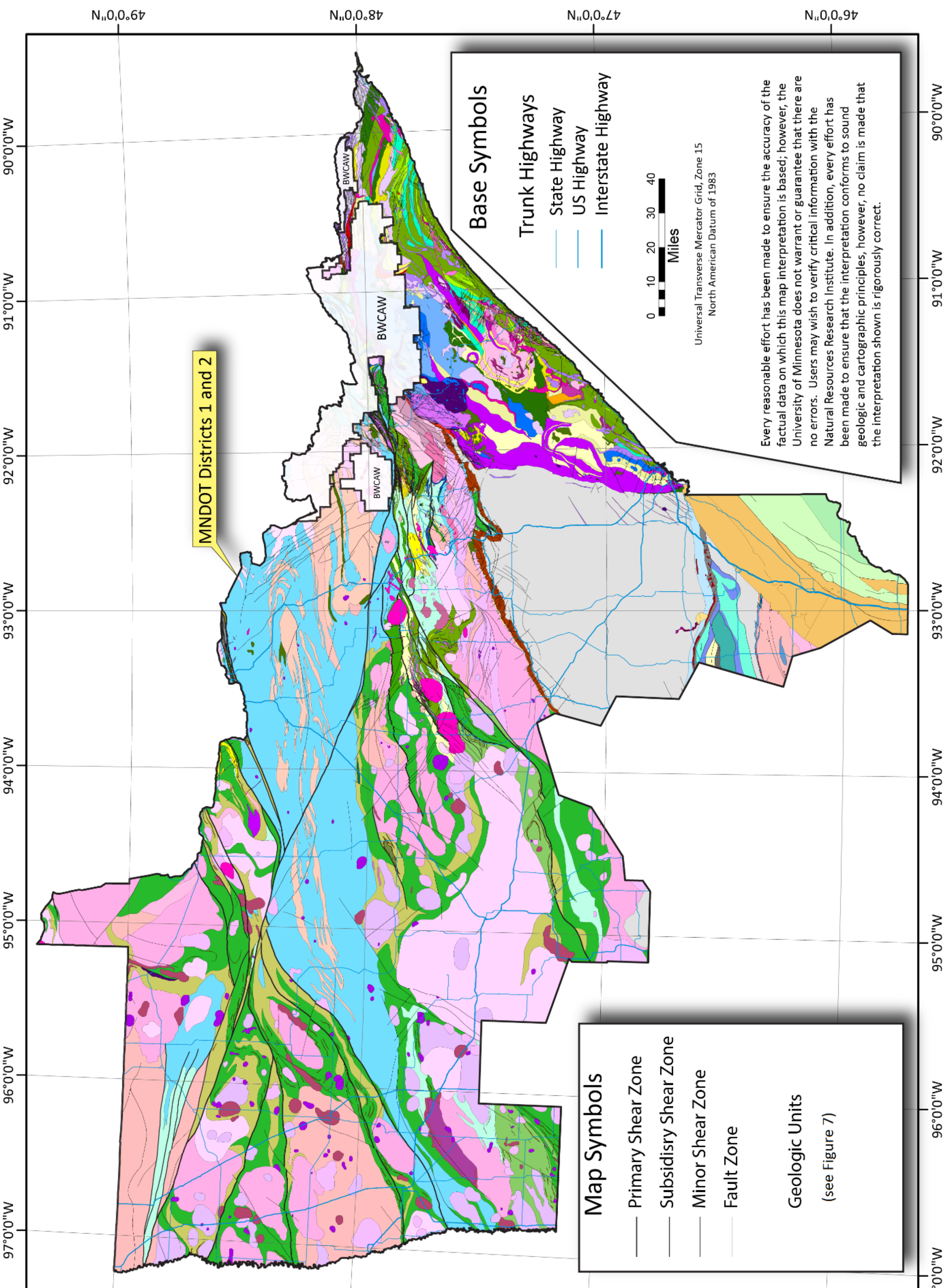


Figure 5. Precambrian bedrock geology map of the study area.

Figure 6. Colorized unit legend of the Precambrian bedrock geology map depicted in Figure 5. Geologic unit PAG rank is given to the left of each subunit.

The methodology used to define the ranking of geologic units is based on the author's 30+ years of geological experience working on the Precambrian geology of Minnesota complimented by >150 years of similar experience by NRRI colleagues. The scheme for ranking geological units (Table 1) was first presented to MNDOT and the TAP in November 2017 and have remained the same since that date. Brief descriptions of the individual geologic unit PAG rankings (see Figure 6) are given below.

Geologic units of Neoarchean age (~2.7 Ga.) fall into 8 categories. Mafic and Felsic volcanic rocks (the "greenstones" of granite-greenstone terranes, are all given a PAG rank of 2, as these rocks typically contain 0.25 – 0.5% disseminated pyrite. Similarly, mafic intrusive rocks, which include synvolcanic sill-like intrusions and late plug-like bodies, typically contain 0.25 – 0.5% disseminated sulfide minerals and thus are given a PAG rank of 2. However, detailed geological mapping in some well exposed areas has shown the presence of specific sulfide-rich mafic intrusive rock units. These units are given a PAG rank of 5 as we know they contain abundant sulfide minerals.

Neoarchean sedimentary rocks include both clastic and chemical varieties. Clastic sedimentary rocks are dominated by varieties of deep-water greywacke-slate (units Ags and Aks) with lesser shallow-water sandstone and conglomerate (units Aas and Acg). All of these clastic sedimentary rocks seemingly have low sulfide contents (nil to 0.25%) and are given a PAG rank of 1. The exception is discrete units of graphitic argillite which are largely known from drill cores. These graphitic units typically contain from 2.0 - >10.0% iron sulfide minerals (pyrite-pyrrhotite-marcasite) and are given a PAG rank of 5. Chemical sedimentary rocks of Neoarchean age are all varieties of Algoma-type iron formations, which form on the seafloor via venting of moderately hot hydrothermal fluids. Such rocks typically contain >1% sulfide minerals and are given a PAG rank of 4. Exceptions include units of unusually sulfide-rich, >10% sulfide, iron formation (units Aifs and Avms) which have a PAG rank of 5.

Neoarchean felsic intrusive rocks, the "granites" of granite-greenstone terranes, are universally low in sulfide content. Such rocks typically contain nil to <0.25% sulfide minerals and are given a PAG rank of 1. Two exceptions to this rule are small dike- and sill-like porphyritic intrusive bodies (units Afp and Aqfp). These two geologic units are typically associated with sulfide mineralized hydrothermal systems and commonly contain ~1% disseminated sulfide minerals. The porphyritic units are given a PAG rank of 3.

Higher-grade metamorphic rocks of Neoarchean age typically contain very low sulfide mineral contents. There rocks are all higher-grade metamorphic (amphibolite-grade metamorphism) equivalents of the geologic units described above. The high temperature associated with this metamorphism can vaporize enclosed sulfide minerals leaving behind sulfide-free rock. The PAG rankings associated with these metamorphic rocks range from 0 to 2 based on field experience with mafic amphibolites (metamorphosed mafic volcanic and intrusive rock units Amm and Aam) retaining a conservative PAG ranking of 2.

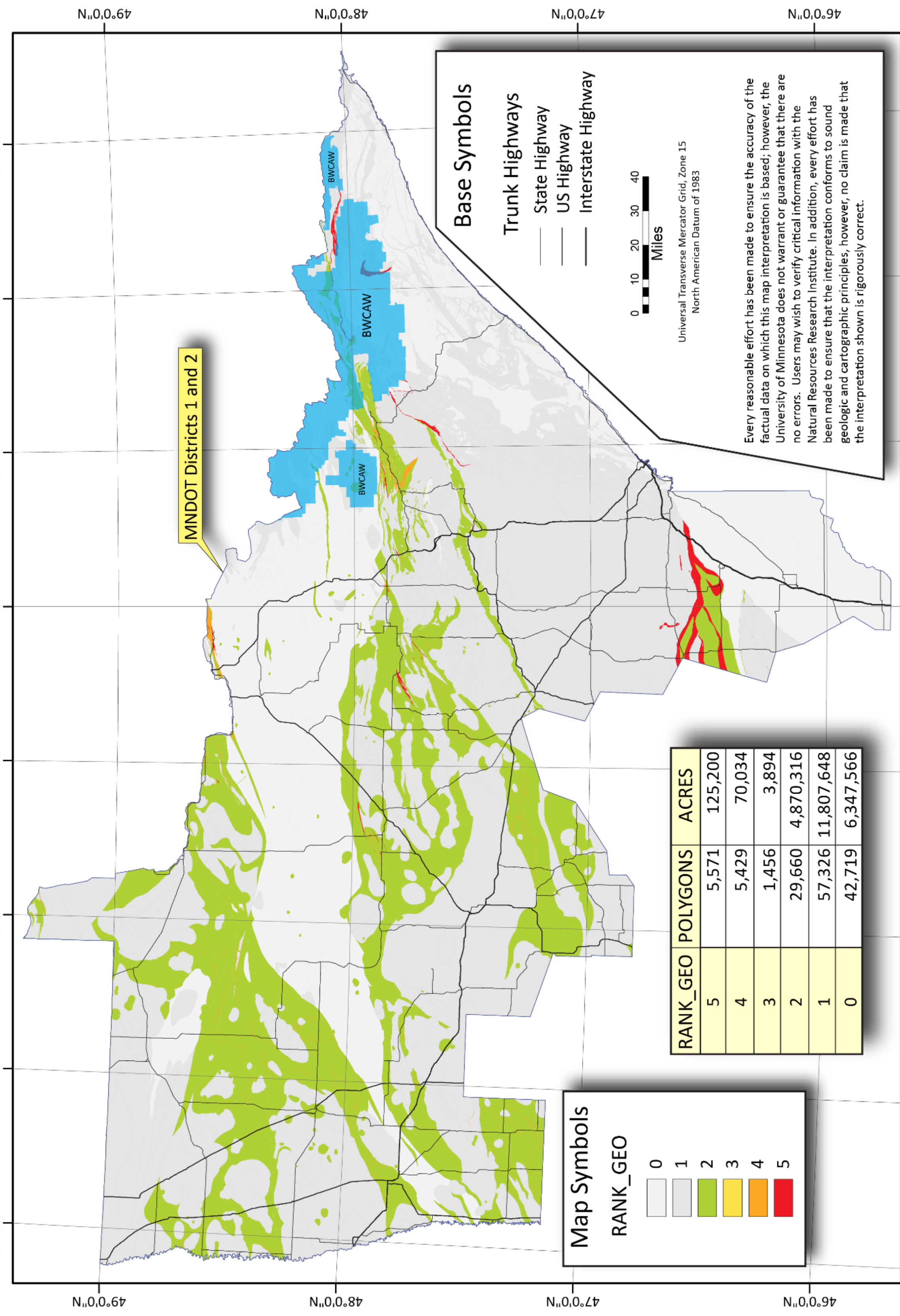
Sheared rocks of Neoarchean age typically contain disseminated sulfide minerals in appreciable amounts (>1% sulfide) and thus have a PAG rank of 4. Discrete zones of sulfideenriched (to >10% sulfide) sheared rocks have been mapped in detail in many areas and these units (Aqv, Aszp, Aszs, Asza, Aszf) have been given a PAG rank of 5.

With the exception of mine pit exposures of the Biwabik Iron Formation on the Mesabi Iron Range, Paleoproterozoic (~1.9 Ga.) rocks in the study area are typically poorly exposed. The lack of true exposure results in the creation of geologic map units based on limited drilling and geophysics resulting in the lumping of rock types together into geological units. These limiting features makes it difficult to estimate a PAG ranking of these Paleoproterozoic rocks. As such, the NRRI has applied our detailed knowledge of PAG ranked Neoarchean geologic units and applied similar rankings to similar rock types. For example, volcanic rocks and mafic intrusions are given a PAG rank of 2, felsic intrusions are PAG ranked 1, clastic sedimentary rocks have a PAG rank of 1 (with a subset of graphitic rocks PAG ranked 5). Chemical sedimentary rock of Paleoproterozoic age include two different PAG rankings. Shallow water Superior-type iron formations (the Biwabik and Gunflint iron formations) typically have low sulfide contents (nil to 0.5%) and have a PAG ranking of 2. Deep-water Algoma-type hydrothermal iron formations in the Paleoproterozoic fold & thrust belt are associated with volcanic rocks and typically contain appreciable amounts of graphite and sulfide minerals. These Algoma-type iron formations are given a PAG ranking of 5.

All Mesoproterozoic (~1.1 Ga.) rocks in the study area are igneous products of the Earth's mantle being partially melted during the formation of the Mid-Continent Rift. The geological end products of this great Earth event was the formation of huge sequences of lava flows and associated deep-seated and near-surface synvolcanic intrusions of the Beaver Bay Complex and Duluth Complex. As well, this great igneous event resulted in the formation of great quantities of sulfide minerals in discrete geological units via the fixation of base (iron-copper-nickel-cobalt) and precious (platinum-palladium-gold-silver) metals to a limited supply of sulfur atoms in early troctolitic magmas of the rift.

The vast majority of the Mesoproterozoic age rocks in the study area are essentially devoid of sulfide minerals and the PAG ranking utilized herein follows this basic fact. All Mesoproterozoic volcanic rocks have a PAG rank of 0 as they are devoid of any sulfide minerals. Early Duluth Complex magmas (the Duluth Complex Granitic and Anorthositic rocks of Figure 6) also have a PAG ranking of 0 as they generally only have trace amounts of the copper sulfide mineral chalcopyrite present. More mafic intrusions within the Mesoproterozoic include the Duluth Complex gabbroic and troctolitic rocks, the hybrid "Ferro" rocks of the Beaver Bay Complex, and a series of miscellaneous intrusive rocks. All of these mafic rocks contain on average a trace amount of sulfide minerals (which can range very locally up to 0.25%) and have a PAG ranking of 1.

Over the last 30 years, detailed geological mapping and drill core logging by NRRI geologists within the Cu-Ni-PGE mineralized zones of the Duluth Complex has resulted in a very detailed geological map depiction of these sulfide bearing rocks. These rock units, the Sulfidic Intrusive Rocks of Figure 6, contain an average of 1-5% sulfide and have a PAG ranking of 5. As well, the sulfidic rock units of the Tamarack Intrusion (Miscellaneous Intrusive Rocks units Mprs and Mptms) are also given a PAG rank of 5.



RANK_GEO	POLYGONS	ACRES
5	5,571	125,200
4	5,429	70,034
3	1,456	3,894
2	29,660	4,870,316
1	57,326	11,807,648
0	42,719	6,347,566

Figure 7. PAG map of the bedrock geologic map units for the study area.

Mineral Occurrences

A "mineral occurrence" is a concentration of a mineral (usually, but not necessarily, considered in terms of some commodity, such as copper or gold) that is considered valuable by someone somewhere, or that is of scientific or technical interest. For this study, four selection sets were queried out of the NRRI's mineral occurrence database to generate the PAG ranked mineral occurrence layer (Table 3). Discrete buffers were created in the GIS around each of the selected data to increase their influence in the PAG model because the identification of all mineral occurrences is limited by exposure of the bedrock to a geologist's eye, i.e., outcrops or drill holes.

Table 3. Details of the selection criteria utilized to generate the mineral occurrence dataset.

TYPE	Iron Sulfide	Other Sulfide	Hydrothermal	Veining
BUFFER (m)	200	200	400	100
PAG RANK	5	4	3	3
Minerals/textures Included in Dataset	Massive Sulfide	Chalcopyrite	Sericite	Quartz
	Pyrite	Pentlandite	Ankerite	Veining
	Pyrrhotite	Sphalerite	Epidote	Breccia
		Bornite	Zoisite	
		Tetrahedrite	Quartz	
		Arsenopyrite	Chlorite	
		Galena	Fuchsite	
		Tahlnakite	Calcite	
		Gold	Tourmaline	
		Silver	Barite	
		Copper	Actinolite	
		Sheared	Albite	
			Adularia	
			Amphibole	
			Garnet	

Field examples of the four types of mineral occurrences that have been utilized in this study are presented in Figure 8, and the final PAG-ranked mineral occurrence map is given in Figure 9.

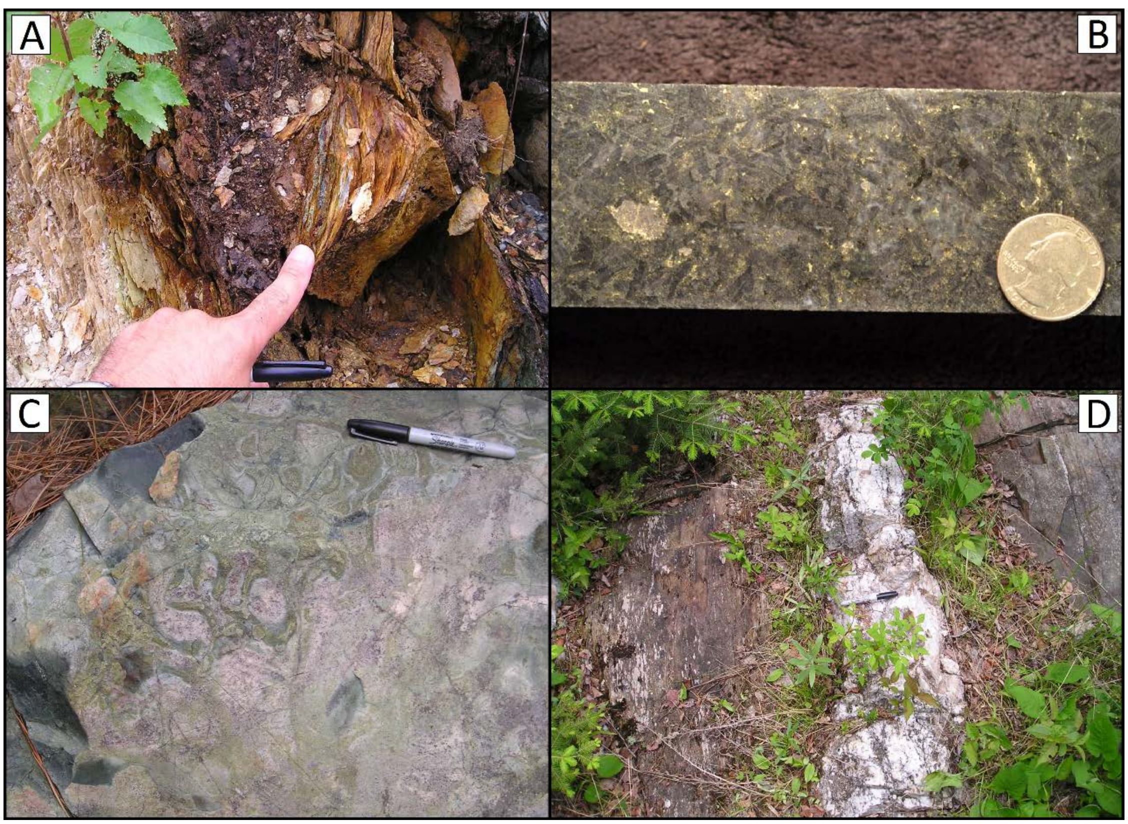


Figure 8. Photographs of the four types of mineral occurrences utilized in this study: (A) Fe-Sulfide: sheared sericite-ankerite-pyrite schist; (B) Other-Sulfide: Drill core with disseminated chalcopyrite in anorthosite; (C) Hydrothermal: Epidote-zoisite-garnet altered pillow basalt; and (D) Veining: Quartz vein in chlorite schist.

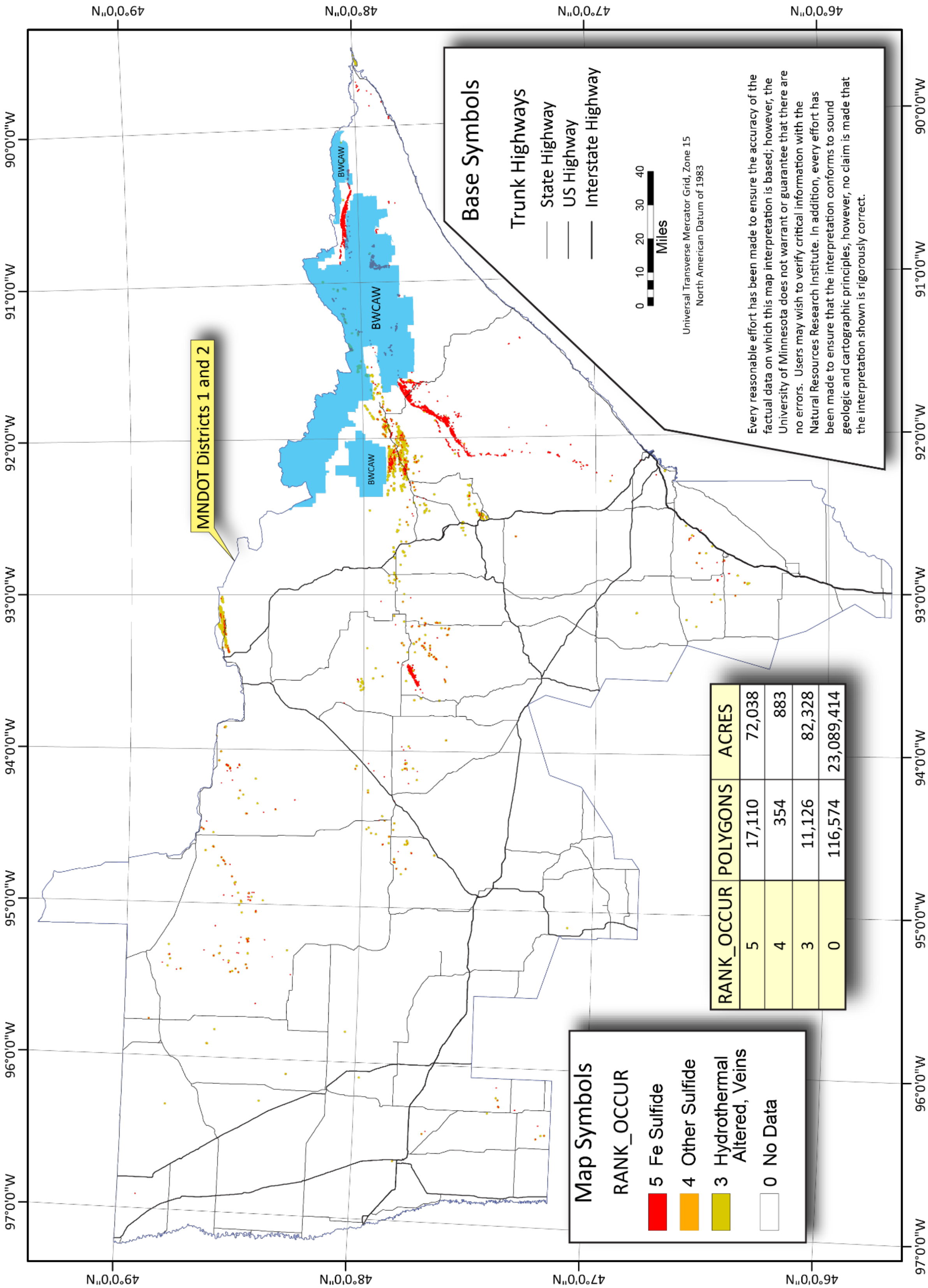


Figure 9. PAG map of mineral occurrences for the study area.

Lithologic Boundaries

The lines on a digital geologic map can tell much of the story of the geology of area, especially if the lines are fully described in the associated GIS attribute table.

For this study, six selection sets that can be associated with hydrothermal addition of sulfide minerals were queried out of the NRRI's geolines database to generate the PAG ranked lithologic boundaries layer (Table 4). Discrete buffers were created in the GIS around each of the selected data to increase their influence in the PAG model. Field examples of four types of lithologic boundaries known to be associated with increased pyrite content are presented in Figure 10, and the final PAG-Ranked lithologic boundary map is given in Figure 11.

Table 4. Details on the geologic lines utilized to generate the lithologic boundaries layer in this study.

LINE_TYPE	MILES	BUFFER (m)	RANK
Subsidiary Shear Zone	766.6	150	5
Minor Shear Zone	234.0	50	4
Primary Shear Zone	1,340.6	200	3
Fault Zones	5,645.8	50	3
Contact: Intrusive	16,453.4	50	2
Contact: Sheared	327.9	25	2
Contact: Stratigraphic	6,353.7	These data not utilized in the PAG model	
Contact: Metamorphic	63.0		
Unconformity	372.0		

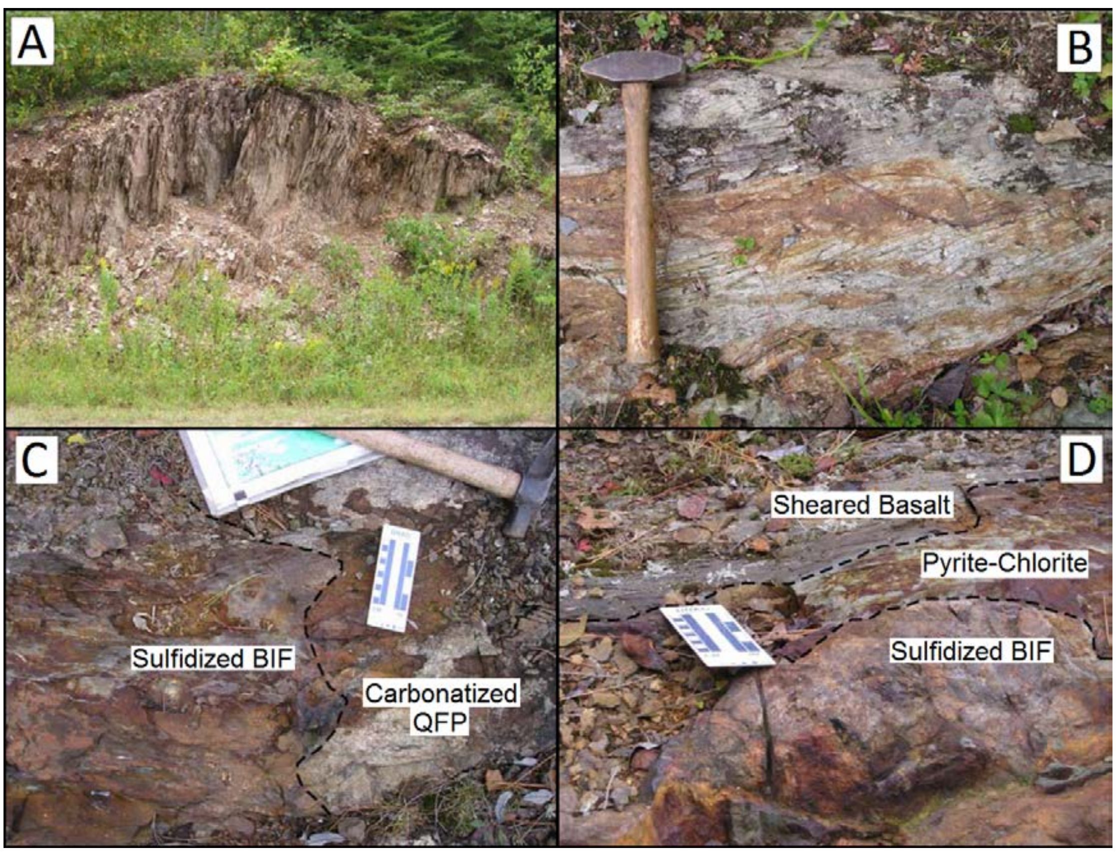


Figure 10. Photographs of four types of lithologic boundaries utilized in this study: (A) Primary Shear Zone: Outcrop of the Mud Creek Shear Zone; (B) Subsidiary Shear Zone: Pyrite-bearing sericite schist; (C) Contact-Intrusive: Sulfidized intrusive contact between iron formation and quartz-feldspar porphyry; and (D) Contact-Sheared: Chlorite-pyrite developed in a sheared contact between basalt and iron formation.

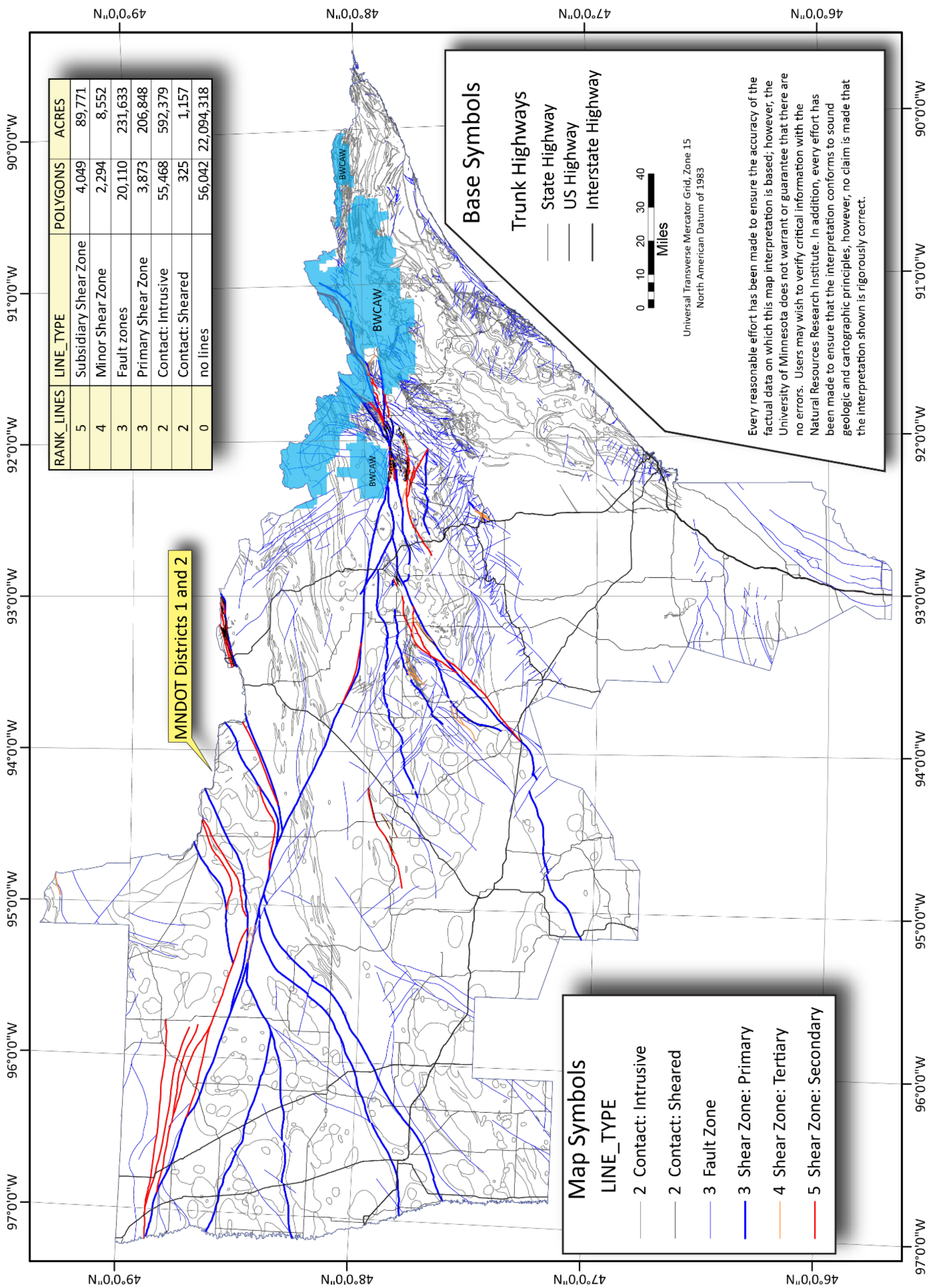


Figure 11. PAG map of lithologic boundaries for the study area.

Depth to Bedrock

The depth-to-bedrock map is the only component of the PAG Map that MnDOT engineers will be using in their GIS-based tool Georilla to initiate consultations with MnDOT geologists on PAG bedrock. In several Technical Advisory Panel meetings for the project, it was determined that a single map depicting a 50-foot depth-to-bedrock cutoff will be used by project engineers in the MnDOT GIS-based Georilla system (Fig. 12). This cutoff was chosen, and will be utilized, from the fact that future MnDOT roadway realignments envisioned in Districts 1 and 2 will rarely, if ever, cut through 50 feet of overburden and expose bedrock that may have PAG minerals.

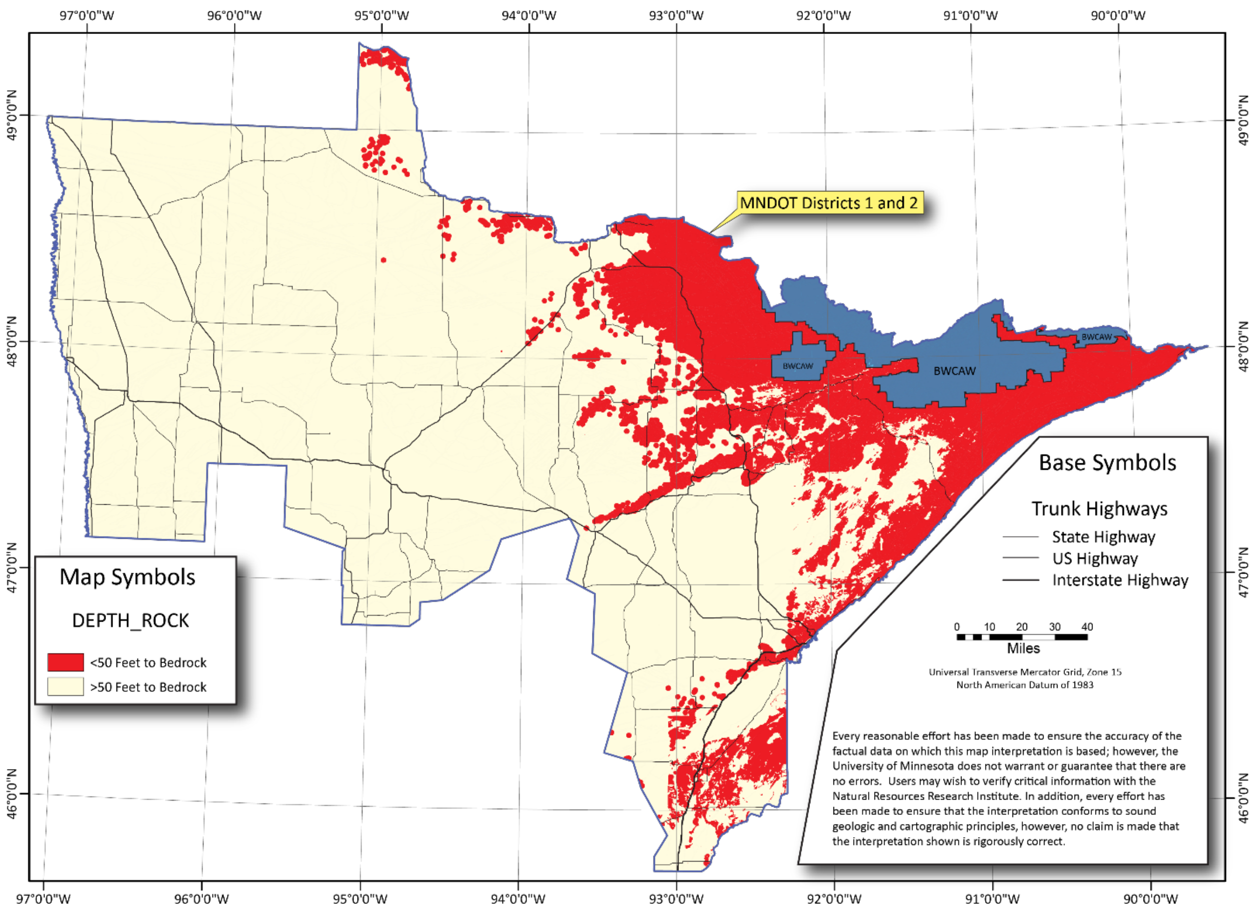
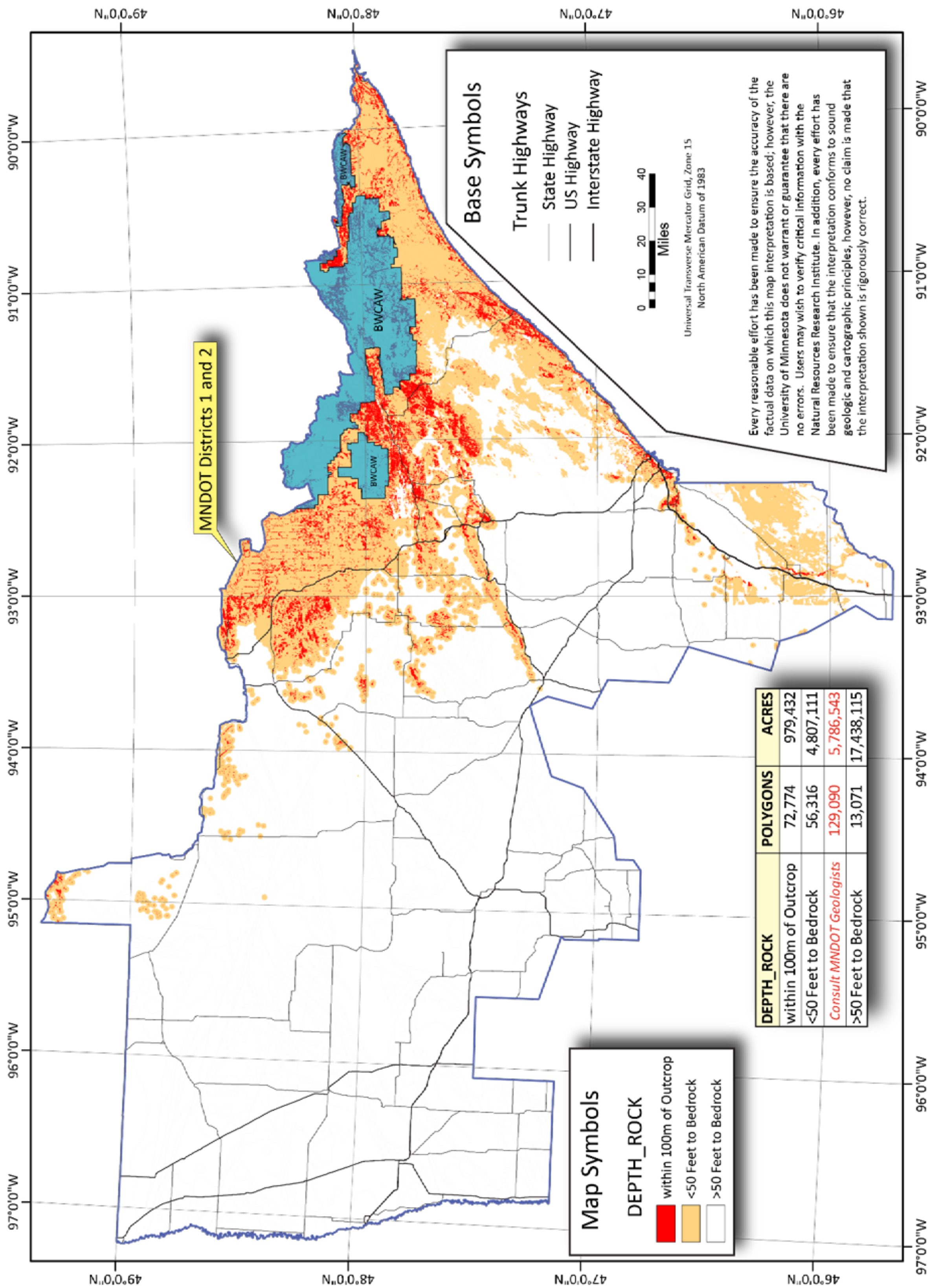


Figure 12. GIS-based map to be used in MnDOT's Georilla system depicting a 50-foot cutoff in the depth to bedrock.

However, the final PAG map utilizes a more detailed depth-to-bedrock map depicting areas: 1) within 100 meters of a mapped outcrop; 2) where the depth to bedrock is less than 50 feet; and 3) where the depth to bedrock is greater than 50 feet (Fig. 13). The more detailed depth-to-bedrock map is the one used in the PAG model (see Fig. 2) that the geologic staff of MnDOT will be using in their internal GIS system.



DEPTH_ROCK	POLYGONS	ACRES
within 100m of Outcrop	72,774	979,432
<50 Feet to Bedrock	56,316	4,807,111
Consult MNDOT Geologists	129,090	5,786,543
>50 Feet to Bedrock	13,071	17,438,115

Figure 13. Depth to bedrock map of the study area.

PAG MODEL

As depicted in Figure 2, the PAG model is composed of four underlying ranked components: bedrock geology (Fig. 7), mineral occurrences (Fig. 9), lithologic boundaries (Fig. 11), and depth to bedrock (Fig. 13). The digitally intersected components have been combined into six different final PAG rankings (SCORE_1 … SCORE_6) in the attribute table (see Table 5) of the PAG map using the method presented in Figure 14.

NUMBER	ITEM	CATEGORY	DESCRIPTION	BUFFER (m)	RANK	ATTRIBUTE COLUMN	ADDITION
IA	Archean Bedrock Geology					RANK_GEO 0 to 5	RANK_123 0 to 15
	i	Volcanic rocks		0	2		
	ii	Clastic sedimentary rocks		0	1		
	iii	Chemical sedimentary rocks	Algoma-type	0	4		
	iv	Mafic intrusions		0	2		
	v	Granitoid intrusions		0	1		
	vi	Felsic porphyries		0	3		
	vii	Migmatitic rocks		0	0		
	viii	Sheared rocks		0	4		
	ix	Graphitic rocks		0	5		
	x	Sulfide-rich rocks	variable rock units	0	5		
IB	Paleoproterozoic Bedrock Geology						
	i	Volcanic rocks		0	2		
	ii	Clastic sedimentary rocks		0	1		
	iii	Chemical sedimentary rocks	Superior-type	0	2		
	iv	Chemical sedimentary rocks	Algoma-type	0	4		
	v	Mafic intrusions		0	2		
	vi	Granitoid intrusions		0	1		
	vii	Sheared rocks		0	4		
	viii	Graphitic rocks		0	5		
	ix	Sulfide-rich rocks	variable rock units	0	5		
IC	Mesoproterozoic Bedrock Geology						
	i	Volcanic rocks		0	0		
	ii	Clastic sedimentary rocks		0	0		
	iii	Troctolitic intrusions		0	1		
	iv	Gabbroic Intrusions		0	1		
	v	Anorthositic Intrusions		0	0		
	vi	Granitoid intrusions		0	0		
	vii	Sulfide-rich rocks	variable rock units	0	5		
II	Mineral Occurrences					RANK_OCCUR 0 to 5	
	i	Fe-Sulfide dominant		200	5		
	ii	Cu-Sulfide dominant		200	4		
	iii	Hydrothermal Alteration		400	3		
	iv	Veining		100	3		
	v	Everywhere else	outside of buffers		0		
III	Lithologic Boundaries					RANK_LINES 0 to 5	
	i	Shear Zone: Primary		200	3		
	ii	Shear Zone: Secondary		150	5		
	iii	Shear Zone: Tertiary		50	4		
	iv	Fault Zone		50	3		
	v	Contact: Intrusive		50	2		
	vi	Contact: Sheared		25	2		
	vii	Everywhere else	outside of buffers		0		
IV	Depth to Bedrock						
	i	Within 100 meters of outcrop	NRRI database	100	5	RANK2ROCK	See Below
	ii	< 50 Feet	Multiple MGS maps		4	RANK2ROCK	
	iii	> 50 Feet	Multiple MGS maps		0	RANK2ROCK	

Rank	Category
0	No known PAG
1	Low PAG
2	Moderately Low PAG
3	Moderate PAG
4	Moderately High PAG
5	High PAG

Composite Score	<100 meters to Outcrop if RANK2ROCK = 5, then	<50 Feet to Bedrock if RANK2ROCK = 4, then	>50 Feet to Bedrock if RANK2ROCK = 0, then
SCORE_1	RANK_123/15	RANK_123/15	RANK_123/30 ← NRRI Recommended
SCORE_2	RANK_123/15	RANK_123/15	RANK_123/45
SCORE_3	RANK_123/15	RANK_123/15	RANK_123/60
SCORE_4	RANK_123/15	RANK_123/30	RANK_123/45
SCORE_5	RANK_123/15	RANK_123/30	RANK_123/60
SCORE_6	RANK_123/15	RANK_123/30	RANK_123/75

Figure 14. Methodology utilized to generate the six different final PAG rankings (SCORE_1 … SCORE_6) in the attribute table of the final PAG map.

Table 5. Description and example of the final PAG map attribute table for two individual polygons.

Columns in the PAG Map Attribute Table

HEADER	DESCRIPTION	EXAMPLE 1	EXAMPLE 2
FID	Polygon ID number	15409	15827
Shape	Type of GIS feature	Polygon	Polygon
MAP_CODE	Geologic unit code	Aszc	Afve
ROCK_DESC	Rock description	Chloritic phyllite-schist	Epiclastic felsic sediment
GEO_SOURCE	Source of the geologic data	NRRI Map 2004/01	USGS Map GQ-1457
OCCUR_PY	Does polygon fall within a Fe-sulfide mineral occurrence buffer?	Yes	
OCCUR_CP	Does polygon fall within a Other-sulfide mineral occurrence buffer?		
OCCUR_ALT	Does polygon fall within a Hydrothermal alteration mineral occurrence buffer?	Yes	Yes
OCCUR_VNS	Does polygon fall within a veining mineral occurrence buffer?		
LINE_TYPE	Lithologic boundary type	Subsidiary Shear Zone	Minor Shear Zone
DEPTH_ROCK	Depth to bedrock	<50 Feet to Bedrock	>50 Feet to Bedrock
RANK_GEO	PAG rank of the geology	4	2
RANK_OCCUR	PAG rank of mineral occurrences	5	3
RANK_LINES	PAG rank of lithologic boundaries	5	4
RANK2ROCK	PAG rank of the depth to bedrock	4	0
Shape_Leng	Polygon perimeter, in meters	115.154902	1085.530801
Shape_Area	Polygon area, in square meters	314.596052	22464.26842
ACRES	Polygon area, in US acres	0.077738	5.551042
RANK_ADD	Value of RANK_GEO + RANK_OCCUR + RANK_LINES + RANK2ROCK	18	9
RANK_123	Value of RANK_GEO + RANK_OCCUR + RANK_LINES	14	9
SCORE_1	Final PAG ranking (0.0 low to 1.0 high) using SCORE_1 method	0.933	0.300
SCORE_2	Final PAG ranking (0.0 low to 1.0 high) using SCORE_2 method	0.933	0.200
SCORE_3	Final PAG ranking (0.0 low to 1.0 high) using SCORE_3 method	0.933	0.150
SCORE_4	Final PAG ranking (0.0 low to 1.0 high) using SCORE_4 method	0.467	0.200
SCORE_5	Final PAG ranking (0.0 low to 1.0 high) using SCORE_5 method	0.467	0.150
SCORE_6	Final PAG ranking (0.0 low to 1.0 high) using SCORE_6 method	0.467	0.120

The acreage outcome of the final six PAG ranking schemes is summarized in Figure 15. The NRRI recommends that MnDOT's geologic staff utilize the SCORE_1 rankings, as this scheme is the most conservative (i.e., has the highest PAG ranks) in PAG rankings. Maps depicting the final six PAG ranking schemes are given in Figures 16 to 21 below.

SCORE_x Bin Range	Color Ramp	Total Acres / bin range / SCORE_x					
		SCORE_1	SCORE_2	SCORE_3	SCORE_4	SCORE_5	SCORE_6
= 1.00		577	577	577	332	332	332
0.90 - 0.99		1,209	1,209	1,209	857	857	857
0.80 - 0.89		11,937	11,937	11,937	7,744	7,744	7,744
0.70 - 0.79		2,177	2,177	2,177	1,339	1,339	1,339
0.60 - 0.69		27,239	27,239	27,239	15,874	15,874	15,874
0.50 - 0.59		14,267	14,267	14,267	8,809	8,809	8,809
0.40 - 0.49		58,198	58,198	58,198	32,614	32,614	32,614
0.30 - 0.39		85,418	82,026	81,975	36,952	36,902	36,902
0.20 - 0.29		403,443	335,705	332,313	140,234	136,841	136,373
0.10 - 0.19		1,191,438	902,345	679,375	713,751	490,780	427,823
0.01 - 0.09		15,389,702	15,750,398	15,976,811	16,227,532	16,453,945	16,517,370
= 0.00		6,038,584	6,038,584	6,038,584	6,038,584	6,038,584	6,038,584

Figure 15. Chart showing the modeled total acres of 12 bin ranges for each of the final six combined PAG rankings. The color ramp shown for each of the bin ranges is the same as depicted in map form in Figs. 16 to 21.

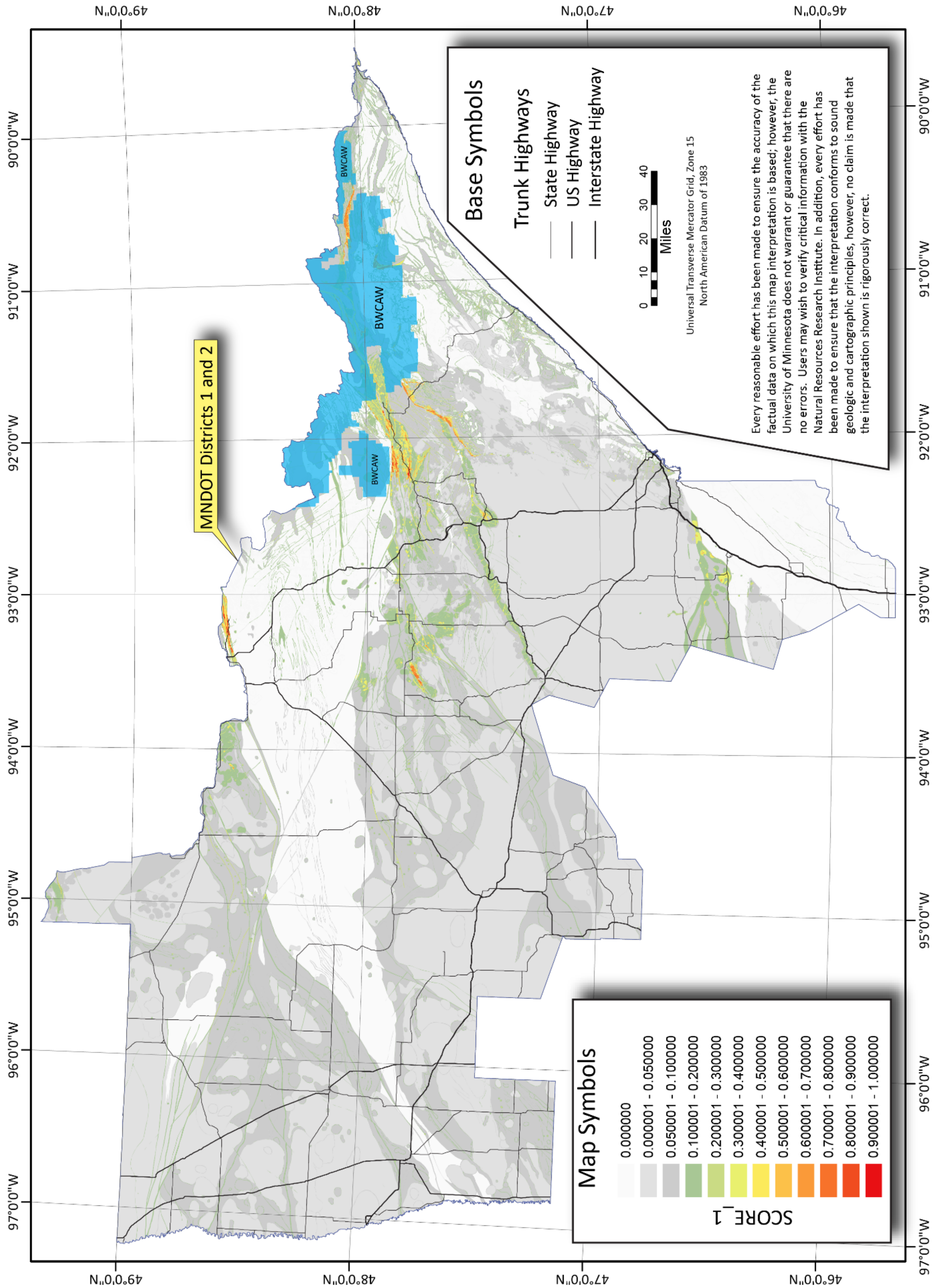


Figure 16. Final PAG map of the modeled ranking (see Fig. 14) of attribute table column SCORE_1.

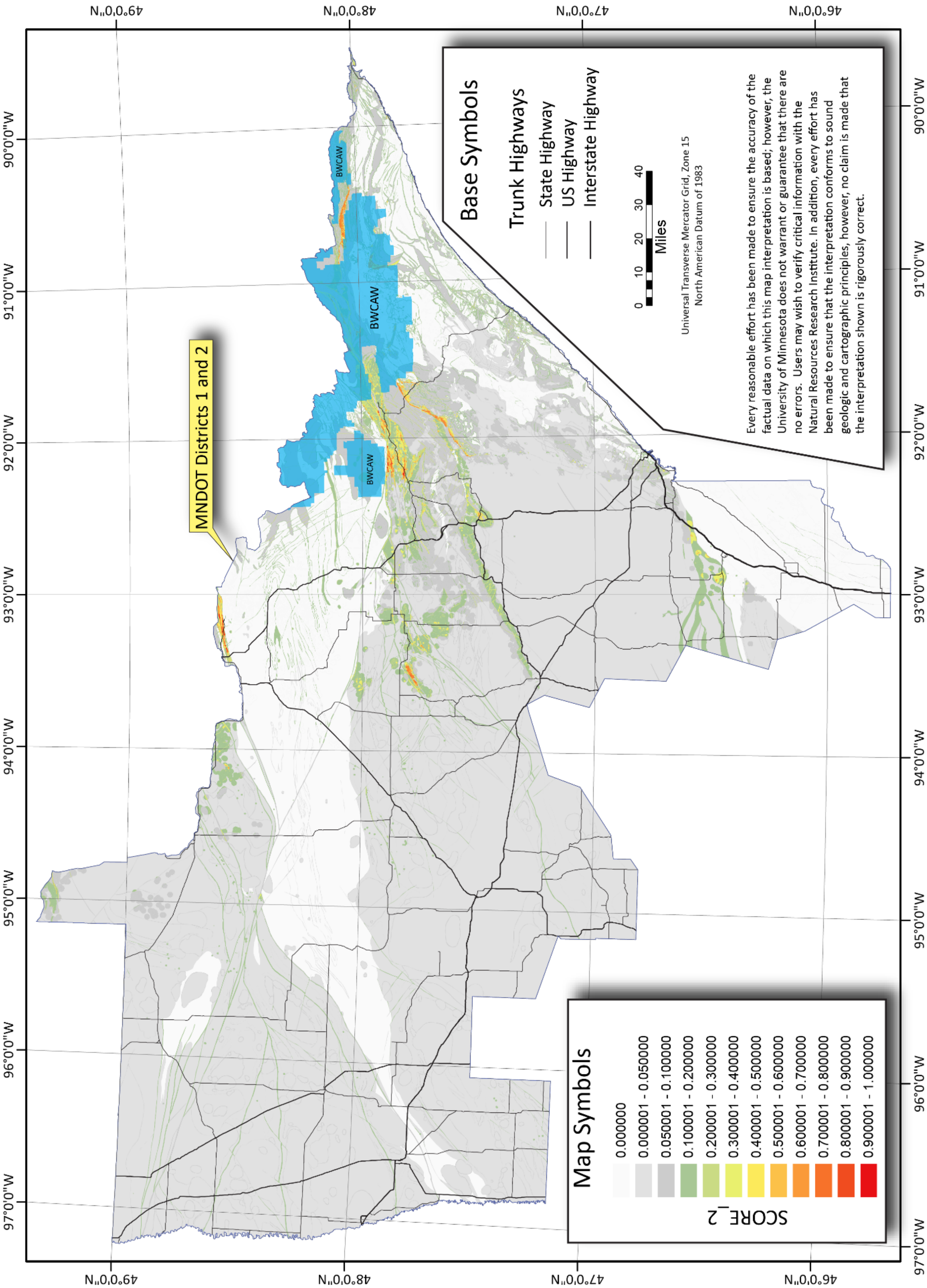


Figure 17. Final PAG map of the modeled ranking (see Fig. 14) of attribute table column SCORE_2.

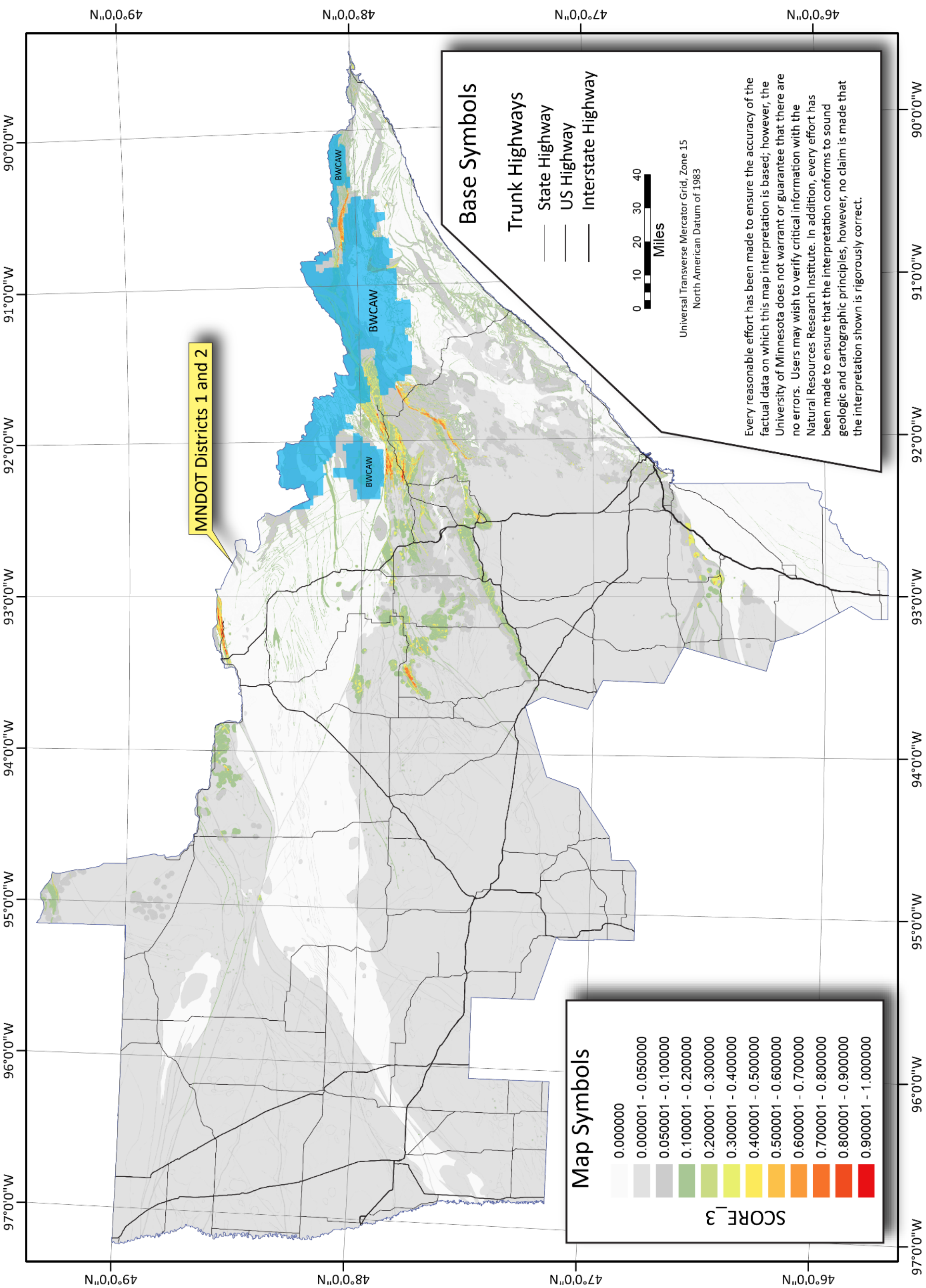


Figure 18. Final PAG map of the modeled ranking (see Fig. 14) of attribute table column SCORE_3.

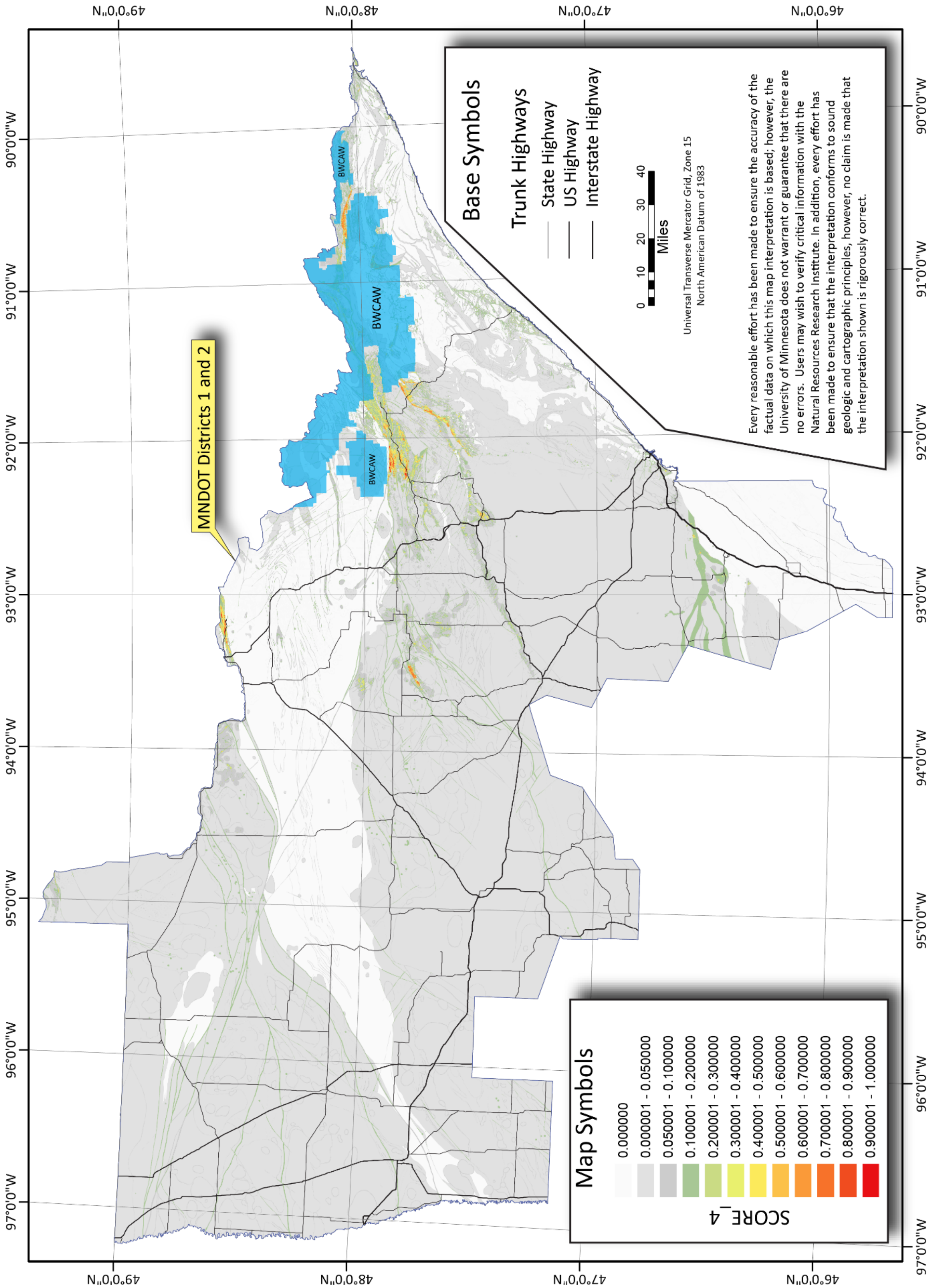


Figure 19. Final PAG map of the modeled ranking (see Fig. 14) of attribute table column SCORE_4.

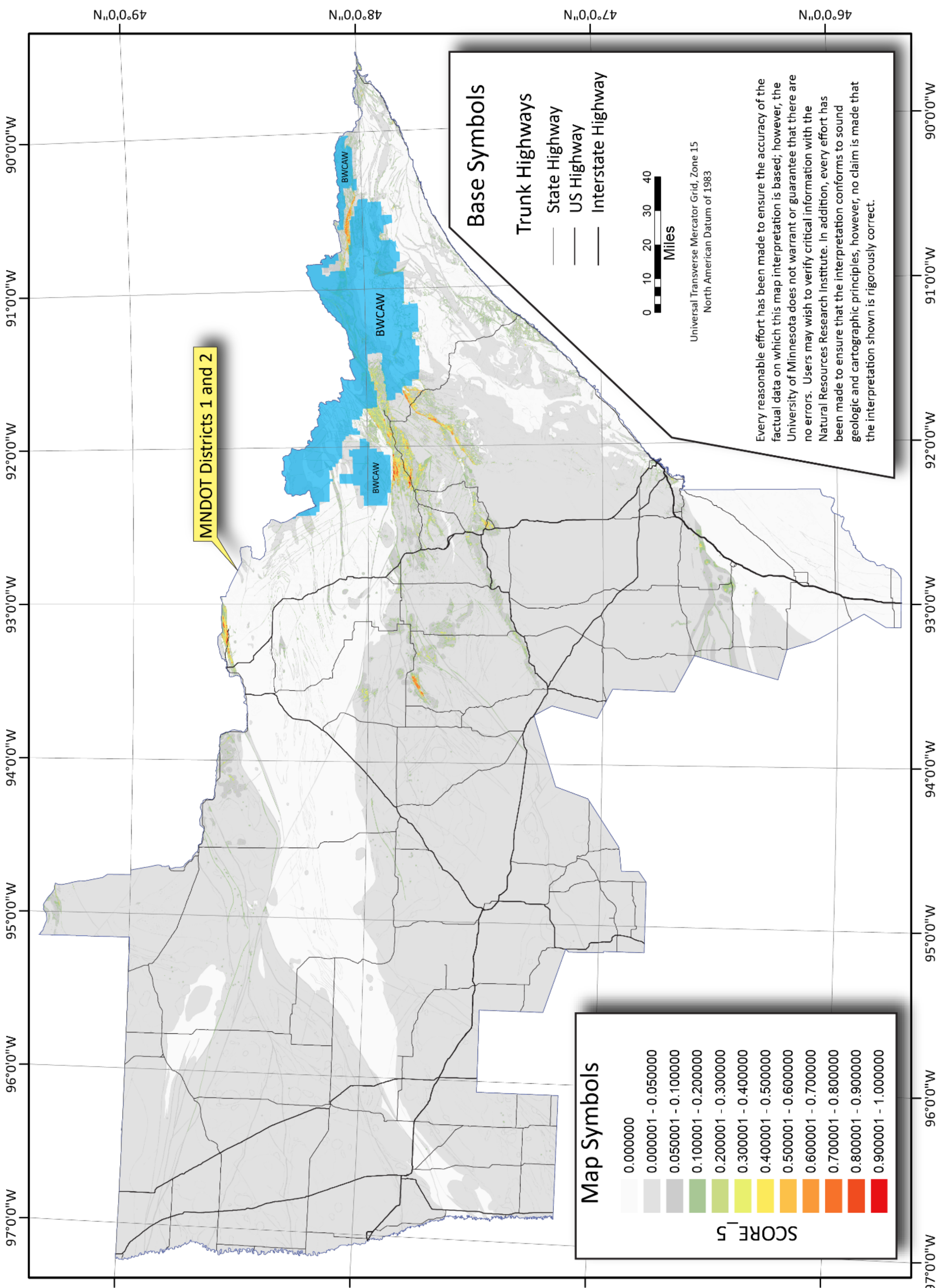


Figure 20. Final PAG map of the modeled ranking (see Fig. 14) of attribute table column SCORE_5.

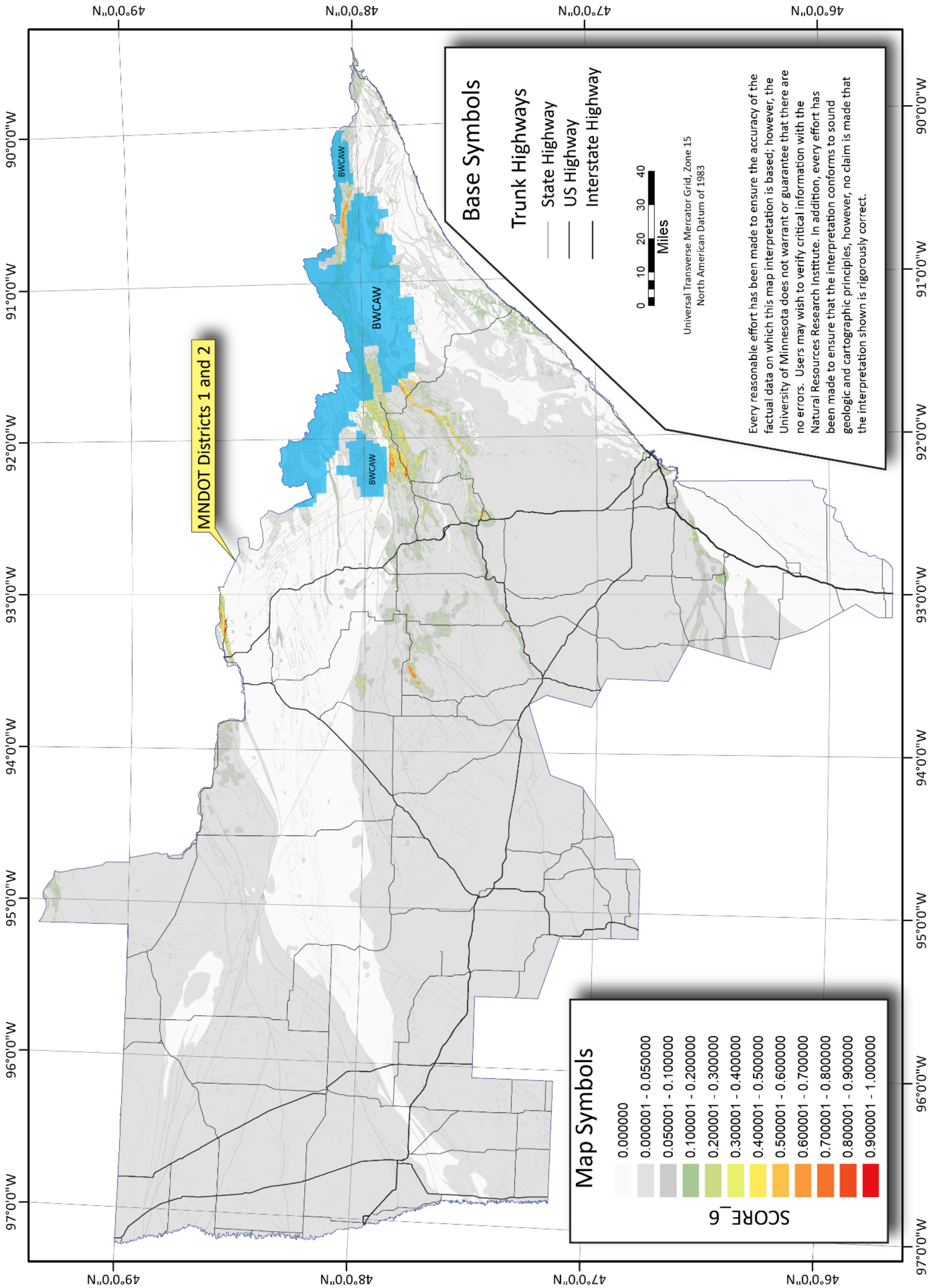


Figure 21. Final PAG map of the modeled ranking (see Fig. 14) of attribute table column SCORE_6.

CONCLUSIONS

The NRRI has created a new GIS-based derivative geological product that MnDOT can use in their Districts 1 and 2 to assess the potential of encountering acid-generating bedrock in roadway construction projects. The final PAG map's 142,161 ranked polygons were created by the intersection of a bedrock geology map (11,482 polygons), a mineral occurrence map (1,516 polygons), a lithologic boundary map (14,407 polygons), and a simplified depth-to-bedrock map (17,551 polygons). Every one of the 142,161 polygons in the final PAG map has the relevant data from each of the four foundation maps stored in the associated attribute table of the final PAG map (see Table 5).

APPENDIX B
FIELD REFERENCE MATERIALS

Field Reference Materials:

Outcrop Description Format

Date:___________________ **Sample #** **S - 499**

Geologist: ____________________

SPxxxx-xx TH xxx Surface Samples

Location Information

PROPERTY: T: ______________

UTME:______________________ R: ______________

UTMN:______________________ S: ______________

ZONE:_________15_________ QTR: ______________________

DATUM:______NAD 83________ QUAD: ______________________

Sampling Information

Rock ( ) Grab ( ) Outcrop : ______________

Float ( ) Channel ( ) Drill Hole: ______________

DDH ( ) Length:_________ Depth: ______________

Sample Use

Chemistry ( ) Thin Section ( ) Polished Section ( ) Geomechanics ( )

Sample Description

Lithology: ____

Alteration: ____

Mineralization: ____

Structure: ____

S - 499

Date:___________________ **Sample #** **S - 500**

Geologist: ____________________

SPxxxx-xx TH xxx Surface Samples

Location Information

PROPERTY: T: ______________

UTME:______________________ R: ______________

UTMN:______________________ S: ______________

ZONE:_________15_________ QTR: ______________________

DATUM:______NAD 83________ QUAD: ______________________

Sampling Information

Rock ( ) Grab ( ) Outcrop : ______________

Float ( ) Channel ( ) Drill Hole: ______________

DDH ( ) Length:_________ Depth: ______________

Sample Use

Chemistry ( ) Thin Section ( ) Polished Section ( ) Geomechanics ( )

Sample Description

Lithology: ____

Alteration: ____

Mineralization: ____

Structure: ____

S - 500

SPxxxx-xx TH xxx Outcrops | OC -

Geologist:________________ UTME:___________; UTMN:___________ of X

Date:_________

Sheet: ________

Mag:

Location:

T: _______
R: _______
S: _______

Samples:

S-_________
S-_________
S-_________

Outcrop Sketch (See Field Notes of Mapper)

Outcrop Condition:

Outcrop Description:

Structures: General Fabric Development: Nil [ ] W [ ] M [ ] S [ ] VS [ ]

Bedding: b1_________; b2_________; b3_________; b4_________; b5_________
Cleavage: c1_________; c2_________; c3_________; c4_________; c5_________
Shears: s1_________; s2_________; s3_________; s4_________; s5_________
Veins: v1_________; v2_________; v3_________; v4_________; v5_________
Joints: J1_________; J2_________; J3_________; J4_________; J5_________
Lineation: L1_________; L2_________; L3_________; L4_________; L5_________
Fold Hinge: h1_________; h2_________; h3_________; h4_________; h5_________
Other:

Sulfide/Oxid. Descr.: Species: _______ Gr. Size: _______ Habit: _______

Matrix: _________________ % of Rx Surf. Area?: ______

Other:

SPxxxx-xx TH xxx Outcrops | OC -

Geologist:________________ UTME:___________; UTMN:___________ of X

Date:_________

Sheet: ________

Mag:

Location:

T: _______
R: _______
S: _______

Samples:

S-_________
S-_________
S-_________

Outcrop Sketch (See Field Notes of Mapper)

Outcrop Condition:

Outcrop Description:

Structures: General Fabric Development: Nil [ ] W [ ] M [ ] S [ ] VS [ ]

Bedding: b1_________; b2_________; b3_________; b4_________; b5_________
Cleavage: c1_________; c2_________; c3_________; c4_________; c5_________
Shears: s1_________; s2_________; s3_________; s4_________; s5_________
Veins: v1_________; v2_________; v3_________; v4_________; v5_________
Joints: J1_________; J2_________; J3_________; J4_________; J5_________
Lineation: L1_________; L2_________; L3_________; L4_________; L5_________
Fold Hinge: h1_________; h2_________; h3_________; h4_________; h5_________
Other:

Sulfide/Oxid. Descr.: Species: _______ Gr. Size: _______ Habit: ________

Matrix: _________________ % Rx Surf. Area?: ______

Other:

By: _______________ **Field Photographs** Roll # [ ]

SPxxxx-xx TH xxx Outcrops

ID	Date	Sheet	Outcrop	Page	Brief Description of Photograph
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38					
39					
40					

By: _______________ **Field Photographs** Roll # [ ]

SPxxxx-xx TH xxx Outcrops

ID	Date	Sheet	Outcrop	Page	Brief Description of Photograph
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Field Reference Materials:

PAG Drilling and Field Procedures

MnDOT Characterization/Drilling- Field Procedures and Info

___________ Project

<u>Contacts:</u>

MnDOT Drilling Project Contact:

MnDOT Project PM:

Drilling Contact:

Consultant Contact:

Field Techs Contact:

<u>Duties/Expectations:</u>

1.) Verify Borehole Locations prior to drilling
    a. Stakes may have been moved or disrupted after surveyors marked locations
    b. Verify/locate using GPS with reasonable accuracy (+/- 5 feet is adequate)
    c. Use other stakes at site for reference, if available

2.) Field Decisions (inclined holes)
    a. Azimuth
        i. Verify azimuth
        ii. Refine azimuth, if necessary, based on outcrops
            1. Perpendicular to strike
        iii. If no outcrops, then use regional trend of formation/member
        iv. Record drilled azimuth on field log or borehole spreadsheet
    b. Abandoning/Re-locating holes
        i. Re-locate PARALLEL to strike
        ii. Stay within 5' of original hole
        iii. Place new lathe with new hole number in sealed hole
    c. Place original survey stake in fresh backfill after sealing original hole location
        i. MnDOT surveyors will survey final borehole location

3.) Maintain boring field log
    a. Cover sheet entries
        i. See MnDOT field log
    b. Water table measurements
        i. Measure at start of day before continuing drilling or prior to sealing
    c. Top of Bedrock
        i. CRITICAL for rock excavation/overburden volume estimates
        ii. For inclined holes, record length of rod from ground to bedrock at 45 degree angle on borehole spreadsheet and/or field log

1. Observe drilling, observe core and communicate with driller to acquire accurate top of bedrock

d. Field Classification
   i. Use MnDOT field log

4.) Core Handling
   a. Handling of core from barrel to box
      i. Ensure that pieces are not out of place
      ii. Mark mechanical breaks induced by drillers
   b. Ensure that dates, depths and hole info are properly marked on blocks, box and field log
   c. Air-dry the core and remind driller to keep dry before and during transport
      i. Place core in core boxes after extraction with no cover and allow to air dry
      ii. Keep dry during on-site storage and during transport
   d. Secure core on site
      i. Keep secured to avoid tampering prior to delivery

5.) Photos
   a. Take photos of filled core box
   b. Take photos of site

6.) Communication
   a. Be available for phone calls and updates

7.) Parking
   a. Contact project manager or drill crew supervisor

8.) Shift information (contact project manager or drill crew supervisor)

9.) Public Interaction
   a. Public is NOT allowed on private property without permission
      i. If permission to enter property is granted then they must remain outside of perimeter/fence constructed by driller
   b. Public is permitted to access State property but must remain outside of perimeter/fence constructed by driller
   c. If public is given permission to enter drilling area then they must be accompanied by MnDOT personnel
   d. If public trespasses and/or breaches perimeter:
      i. Inform them of violation and ask them to leave area
      ii. Call authorities if they refuse to leave

10.) Media Inquiry
   a. Refer to Project Manager
      i. Media may not enter private property unless given permission by property owner
      ii. Media may enter State land but are not allowed to cross drilling perimeter
      iii. Media may enter drilling perimeter if cleared by MnDOT Public Relations in St. Paul and/or accompanied by MnDOT personnel

Field Reference Materials:

Trench Template

Project: **Project Location:** **Project Number:**	**Log of** **Trench:**

Date(s) Excavated:	Weather: **Degrees F**	Logged By:	Excavation Backfill:
Approximate Measurements (feet): (Length) (Width) (Depth)			Excavation Alignment:
Excavation Equipment:	Excavation Contractor:	Groundwater Encountered?	Groundwater Depth (ft):
Approx. Location:	Coordinates: **N:** **E:** **N:** **E:**		Approx. Surface Elevation (feet msl):

Material Description	Samples	
		Choose image

Trench Excavation Cross-section

looking ______________ (Length)

Ground Surface

(Depth)

5 feet

5 feet

Notes:

For MnDOT Geotech Use

*adapted from a form used by NOVA Consulting

Field Reference Materials:

Modal Percentages

Geology 222 Laboratory
"Granites"

Examine one rock from each of the following three groups.

(a) *JB-10 or *WS-19

(b) *W-11 or *W-12

(c) *JB-8 or *WS-13

Describe the hand specimen including texture, mineralogy, and field name. Describe the thin section including mineralogy, estimated mode (volume percent for all minerals present), IUGS classification (based on volume percentages of quartz, alkali feldspar, and plagioclase normalized to 100%), grain size, texture, etc. Please include a labeled photomicrograph for each rock to improve your description and to let me know what you are seeing. Prepare a short summary for each rock with this information. Be sure to include brief reasons (color, form, optical data, texture, etc.) for your mineral identifications. Lab reports should be submitted as files via Moodle, preferably as a single .pdf format file. If you need to send several files, put them all in one folder and use the "Compress" command to create a single ".zip" file of the folder and all its contents. Your filenames should begin with your initials or your name, *e.g.* "JBB_Granites.pdf".

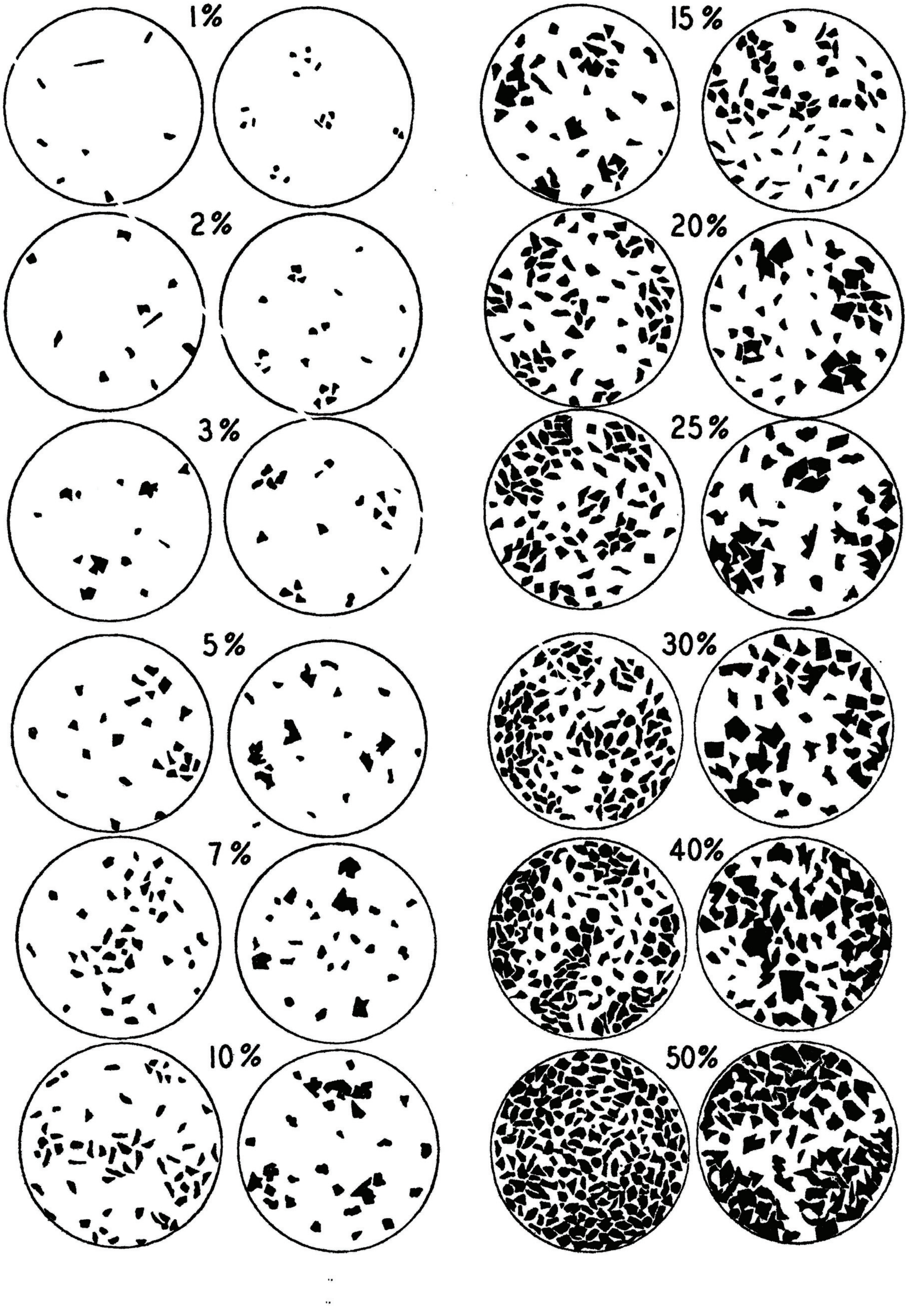
(Note: The dark minerals in group (c) are aegirine (=augite with acmite component) and arfvedsonite (=hornblende with riebekite component).

Additional advice:

To name an igneous rock, you must distinguish between alkali feldspar and plagioclase feldspar. If you have a single (not perthite) potassium feldspar ("K-spar"), it will be either sanidine (volcanic rocks only), orthoclase, or microcline. The difference is ordering of Al and Si on the tetrahedral sites of the feldspar structure. In most cases, there will be either microcline or orthoclase, but not both. Microcline "tartan" twinning can look many ways, depending on the orientation of the grain. Orthoclase "hides" in granitic rocks and can be confused with quartz. An interference figure may help tell quartz from orthoclase. Perthite (and anti-perthite) count as alkali feldspar. Perthite will be a mixture of orthoclase and albite or of microcline and albite.

The mode of a rock is the volume percentages of all the minerals. For each mineral, you should list its volume percentage, and the total should be 100%.

When you include a photomicrograph, be sure to include a scale bar or to give the width of the field of view. Stating the magnification is not particularly meaningful if the document can be viewed at different magnifications on a screen or printed at different scales. The same applies to giving the objective lens information. There are other lenses in addition to the objective lens that affect the magnification, as does the screen magnification.



Modal percentages. Modified from Terry and Chillingar (1955).

American Mineralogist, Volume 70, pages 1318–1319, 1985

Comparison chart for estimating volume percentages of constituents in rocks and concentrates in the range of 1.0 to 0.1 volume percent

JEFFREY C. REID

ARCO Resources Technology
P.O. Box 2819, Dallas, Texas 75221

Abstract

Charts were prepared to aid the visual estimation of trace and accessory constituents in the range of 1.0 to 0.1 volume percent. The charts assist accurate and consistent estimates in this range for hand specimens, microscope slides, and heavy mineral concentrates. Applications include economic geology, sedimentology, and petrology.

Chart documentation

The visual estimation of the volume percent of accessory and trace minerals is important in economic geology, sedimentology, and petrology. Most workers tend to overestimate small percentages (particularly in the case of highly conspicuous minerals like mica); comparison with these charts may help to reduce such errors.

Previous charts (Folk, 1951; Shvetsov, 1954; Terry and Chilingar, 1955) aided visual estimates of essential constit-

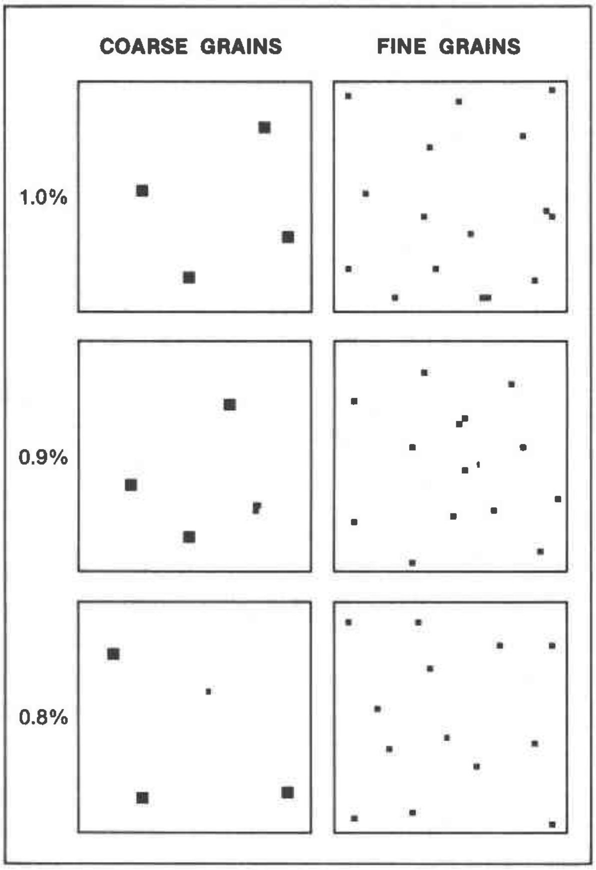


Fig. 1. Comparison chart for estimating percentage composition in the range of 1.0 to 0.8 volume percent for coarse and fine grains.

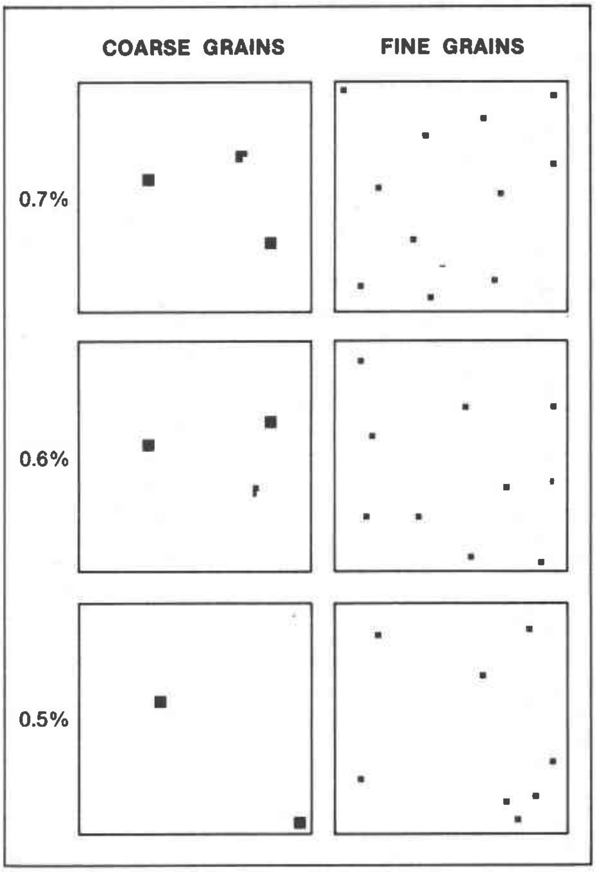


Fig. 2. Comparison chart for estimating percentage composition in the range of 0.7 to 0.5 volume percent for coarse and fine grains.

0003–004X/85/1112–1318$02.00

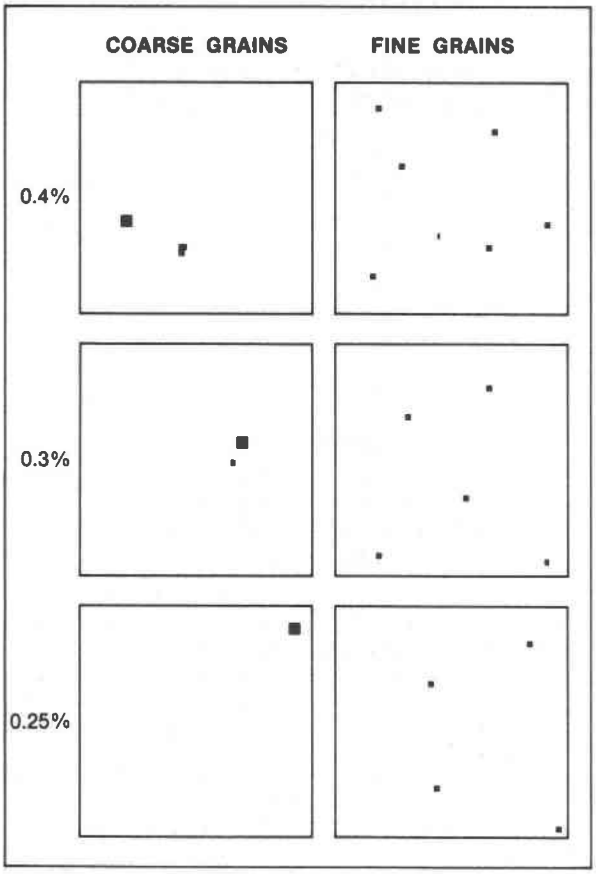


Fig. 3. Comparison chart for estimating percentage composition in the range of 0.4 to 0.25 volume percent for coarse and fine grains.

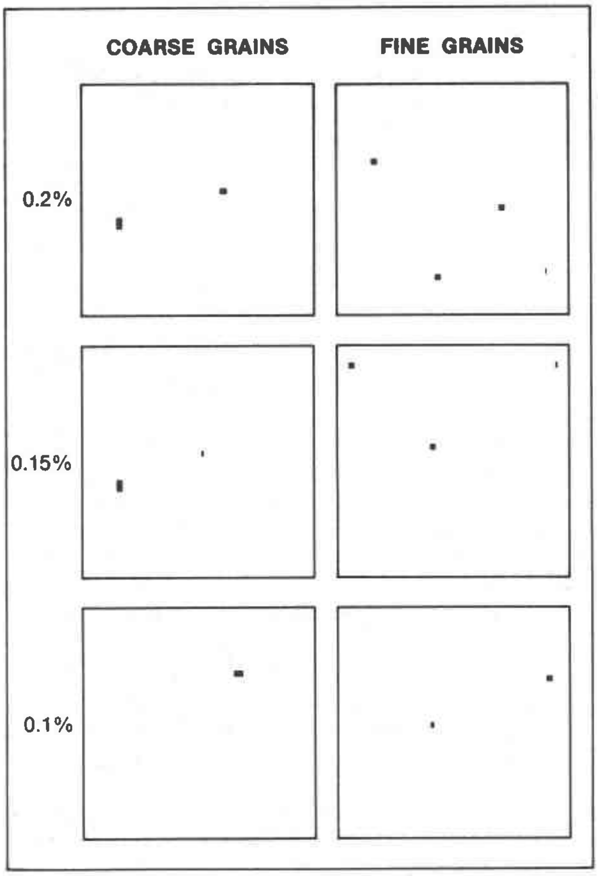


Fig. 4. Comparison chart for estimating percentage composition in the range of 0.2 to 0.1 volume percent for coarse and fine grains.

uents in the range of 1.0 to 50.0 volume percent. The accompanying charts representing various percentages of dark grains on a light background (Figs. 1–4) will aid the visual estimation of trace and accessory minerals in the range of 1.0 to 0.1 volume percent. The width of the original charts approximated common diameters of drill core, and of heavy mineral concentrate trays. Applications include drilling, stream sediment concentrate surveys, sedimentology, and petrographic studies where accurate and consistent values are required for trace and accessory constituents. The charts can be used with either hand specimens or microscope slides.

Readers may wish to prepare negative versions of the charts for light-colored crystals on a dark background. A limited number of these are available from the author.

The charts were drafted by shading the appropriate number of squares on 10 × 10 to 1/2-inch graph paper. The original illustrations contained 40,000 squares. The grains were distributed by a dartboard approach.

Acknowledgments

The author expresses thanks to H. Powell for typing the manuscript, and to S. Miyazaki for drafting the charts. Appreciation is expressed to ARCO Resources Technology for permission to publish this paper. H. Polcheau provided constructive suggestions.

References

Folk, R. L. (1951) A comparison chart for visual percentage estimation, Journal of Sedimentary Petrology, 21, 32–33.

Shvetsov, M. S. (1954) Concerning some additional aids in studying sedimentary formations: Bull. Moscow Soc. Naturalists (Byulleten Moskovskogo Obshchestva Ispytateley Prirody), Pub. Moscow Univ., Geol. Sect., 29, 61–66 (in Russian), not seen.

Terry, R. D. and Chilingar, G. V. (1955) Summary of "Concerning some additional aids in studying sedimentary formations" by M. S. Shvetsov. Journal of Sedimentary Petrology, 25, 229–234.

Manuscript received, February 28, 1985;
accepted for publication, July 25, 1985.

Field Reference Materials:

PAG Sample Preparation Procedure

1. Cut all core lengths in half longitudinally.
    a. This was completed using a water-cooled diamond continuous saw.
2. Cut core transversely at increments of 5 feet.
3. Name each sample using the following scheme:
    a. *Boring ID – top of sample interval - bottom of sample interval*
    b. Example of sample from boring T01 from 7 to 12 feet: T01-7.0-12.0
4. Bag and weigh one of the core halves.
    a. Other half of core is stored for any future need.
5. Crush each sample to >70% passing a #10 sieve (2mm).
    a. Prior to crushing sample, crush barren material to clean crushing jaws.
        i. Quartz or quartzite are acceptable material.
    b. Feed sample into crusher making sure to not overfill crusher.
    c. Sieve and weigh -#10 material.
    d. If <70% of material is -#10, pass the +#10 material through crusher.
    e. Repeat previous two steps until >70 are -#10.
    f. Bag and weigh -#10 material.
    g. In a separate bag, store +#10 material for any future need.
6. Split sample using a riffle splitter to less than 1000 grams.
    a. Store the unused -#10 material for any future need.
7. Pulverize -#10 material using a puck mill to >85% passing a #200 sieve (75 µm).
    a. Due to the capacity of the puck mill, pulverize material in approximately 50 gram batches.
    b. In order to decontaminate puck mill between samples:
        i. Wipe the puck mill clean.
        ii. Pulverize a barren material (e.g. quartzite)
        iii. Wipe the puck mill clean.

APPENDIX C
DE MINIMIS DOSING CALCULATIONS

Determining the maximum sulfur concentration allowed for a 10 PAG:1 Limestone mitigation

Assumptions:

NP of Limestone, pure calcite		1000 T/kT	
CCE		0.9 unitless	
Mass of PAG material	10x	Tons	
Mass of NP Providing material	x	Tons	(where X is a variable to be calculated)
NNP goal (NP-AP)		24 T/KT	12, with SF of 2

For a mix of materials, the weighted average is used.

AP Limestone		0 T/kT	
NP Limestone		900 T/kT	(1000 T/kT)x(0.9)
NP of PAG rock		0 T/kT	
AP of PAG rock - calculated below	Y	T/kT	(where Y is a variable to be calculated)

Material	Mass	NP	AP	% of total mass	NP weighted	AP weighted
Limestone	x	900	0	9%	81.8181818	0
PAG material	10x	0	Y	91%	0	Y*0.91
				Sum	81.8181818	Y*0.91

NNP goal 48 (which is 24 T/kT, applying a SF of 2)

NNP goal = 48 = NP - AP

NNP goal = 48 = 81.81 - (Y)x(0.91)

Solving for Y:

Y = (81.81-48)/(0.91)

Y=37 T/kT of AP for PAG

Since AP = (31.25) x (wt. % S), we can solve for the percentage of sulfur needed to correspond to 68 T/kT

wt % S = (37)/(31.25) = ~1.2%, rounded down to 1.0% sulfur allowable in PAG rock under de minimis conditions
to be managed preemptively using a 10:1 PAG to Limestone mixing ratio.

APPENDIX D
GEOSTATISTICAL EVALUATION SUMMARY MEMORANDUM

Technical Memorandum

To: Jason Richter, Minnesota Department of Transportation
From: Barr Engineering Co.
Subject: Eagle's Nest Geostatistical and Sample Number Analyses
Date: 8/13/2018
Project: 23621275.00

This memorandum summarizes two methods of statistical evaluation performed on the geochemistry data collected as part of the MnDOT Eagle's Nest project to retrospectively evaluate optimal sample frequency for that project area, and to inform sampling frequency for future projects that may encounter potentially acid-generating rock.

This memorandum was prepared as part of a larger effort to develop a MnDOT Guidance Document for dealing with Potentially Acid-Generating (PAG) Materials. Several considerations related to sampling frequency will be included in the PAG Guidance Document, including variability among and within geologic units, physical orientation of lithological units, and relative risk of specific features. These items are not included in this document, but will be provided as context within the site evaluation and sampling frequency discussions in the final PAG Guidance Document.

Briefly, the two methods include a geostatistical analysis, which evaluates spatial variability, and a sample number statistical evaluation, which is spatially independent. Both methods consider the individual rock units separately. This memorandum is organized in three main sections: the geostatistical analysis methods and results, the sample number methods and results, and a comparative summary of the two methods. Critical assumptions inherent in these evaluations include:

- Analytical data were collected from specific geologic formations in a specific location. They may not be representative of different formations, or even the same formation in a different location.
- Each method has specific assumptions about the nature of the data distribution (i.e., normal, log-normal, other) that are reflected below.
- In some cases, the number of samples per geologic formation was insufficient to perform analyses.

Geostatistical Analysis: Introduction

This section of the memorandum describes the methods and results of the geostatistical analysis of the 2015 Eagle's Nest drilling dataset (Heine et al., 2017) conducted for the purpose of estimating optimal sample spacing for future projects involving excavation of potentially acid-generating rock in Minnesota. Parameters analyzed included percent sulfur content, neutralization potential, and paste pH. A fourth parameter, fizz test rating, was considered for analysis but not included because it is a discrete (i.e., not continuous) variable.

Based on the number of available data points, only the Soudan Iron Formation and dacite rock types were evaluated. The results of the analysis suggest an optimal downhole (vertical) sample spacing of approximately 8 feet in the Soudan Iron Formation and 11 feet in the dacite. Parallel to the 36-foot-wide road alignment, the results of the analysis suggest an optimal sample spacing of approximately 350 feet in the Soudan Iron Formation and 450 feet in the dacite. The data parallel to the alignment showed less spatial correlation than the downhole data.

This portion of the memorandum is organized into the following sections: presentation of methods, dataset description, downhole spatial evaluation, along roadway alignment spatial evaluation, and a summary of results.

Geostatistical Analysis: Methods

Geostatistics is a branch of statistics that accounts for the spatial variation between data points. The basic assumption of geostatistical analysis is that samples collected closer together are more similar than samples collected farther apart. This relationship between similarity and proximity is called spatial correlation, and geostatistical analysis can be used to quantify the scale of this spatial correlation to provide a basis for recommending an optimal sample spacing. Geostatistical analysis is not useful if the data do not show spatial correlation.

The variogram (also referred to as the "semivariogram") is a geostatistical tool that is used to quantify the scale of spatial correlation (Olea, 2017). The variogram is a relationship between variability and spacing for unique data pairs. A conceptual variogram is shown on Figure 1 below. The sill of the variogram is theoretically equal to the variance of the population.

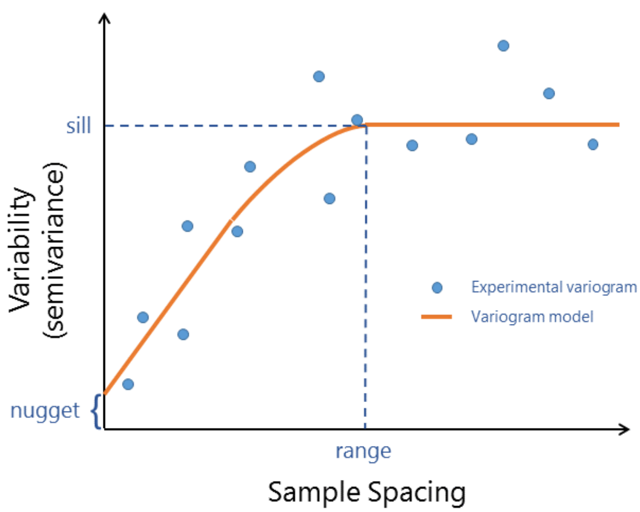


Figure 1 Conceptual Variogram

The experimental variogram (the individual points on Figure 1 above) is constructed using the following procedure:

1. Compute the semivariance for all unique data pairs in the dataset. The semivariance is one-half of the squared difference of the two sample values for each data pair.
2. If the variogram is to be anisotropic (i.e., directionally-dependent), filter the set of semivariances to only include pairs of points that are oriented relative to one another in the desired direction(s).

3. Group together pairs of points that are separated by similar distances into bins and compute the average semivariance for the group. Clearly, the final result will be sensitive to the number of bins used. Too many bins can result in a noisy variogram that doesn't appear to mimic one of the theoretical models, while too few bins may result in too much smoothing of the data. The optimal number of bins is typically left up to the analyst's judgement and determined on a trial-and-error basis. One rule of thumb is to try to have 20-30 data pairs per bin (ITRC, 2016).
4. Plot the average semivariance for each bin versus the nominal point spacing for each bin.

Once the experimental variogram has been constructed, a theoretical variogram model is fit to it. Figure 2 below shows 6 common variogram models. The range, sill, and nugget parameters are adjusted until a reasonable fit is achieved. The choice of the most appropriate model and the determination of the "best" fit to the experimental variogram are both subjective and are therefore dependent on the professional judgment of the modeler. The Stanford Geostatistical Modeling Software (SGeMS) (Remy et al., 2009) was used to generate the experimental variograms for this analysis. SGeMS includes an interface for fitting the theoretical model to the experimental variogram, but the goodness of fit can only be assessed visually. For this analysis, the experimental variograms were exported from SGeMS and the best model fit was determined using the automated inverse optimization software PEST (Watermark Numerical Computing, 2005; 2016). PEST minimizes the sum of squared weighted differences between the experimental variogram values and the model values at the same sample spacings. Weights were assigned based on the number of data pairs used to compute each experimental variogram value (Webster and Oliver, 2007).

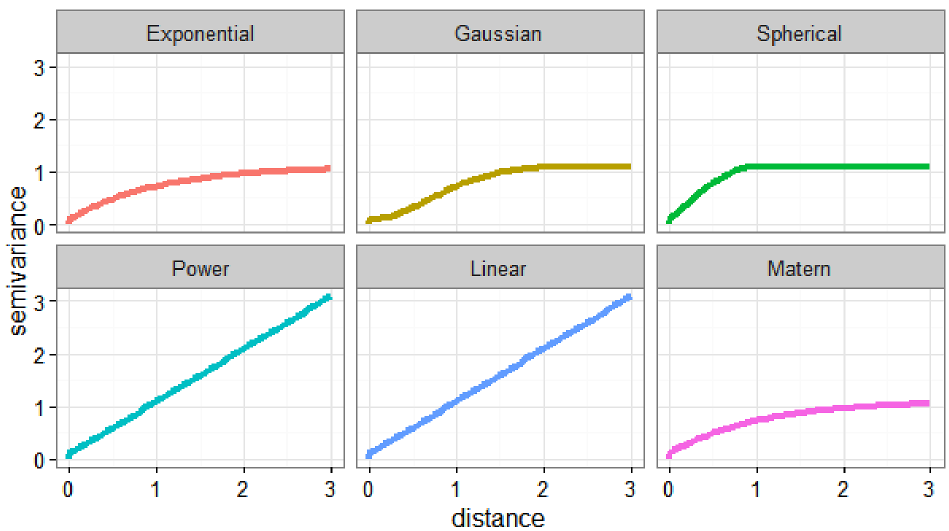


Figure 2 Variogram Models (ITRC, 2016)

The range of the variogram model is equivalent to the scale of spatial correlation. At sample spacings smaller than the variogram's range, variability and sample spacing are correlated. At sample spacings larger than the variogram's range, variability and sample spacing are no longer correlated. Redundant sampling occurs when samples are spaced much closer together than the correlation scale; i.e., at distances where the data are strongly correlated in space. The correlation scale therefore informs the choice of an appropriate minimum sample spacing to avoid collecting strongly spatially correlated data. A conservative (i.e., tending towards the collection of more samples) rule-of-thumb is to use half of the scale of spatial correlation as the sample spacing (ITRC, 2016).

Note that the variogram is a site-specific relationship. When using this approach, the best results are obtained when data are available from the site in question.

Geostatistical Analysis: Dataset

The Eagle's Nest dataset consists of 677 individual samples from 131 borings, the vast majority (95%) of which were drilled at an angle of approximately 45 degrees below horizontal. Table 1 below summarizes the sample data by rock type.

Table 1 Parameter Values by Material Type

Material Type	Count	Weight % Sulfur			Neutralization Potential[1]		Paste pH	
		Range	Mean	Non-detect Count	Range	Mean	Range	Mean
Soudan Iron Formation	318	<0.01 – 10.6	0.34	24	2 – 191	17.9	5.1 – 10.2	8.7
Dacite	273	<0.01 – 0.87	0.10	17	2 - 185	46.0	8.0 – 9.9	9.5
Mafic Volcanics	61	<0.01 – 0.30	0.06	22	15 – 155	46.4	8.0 – 9.7	9.0
Metadiabase	20	<0.01 – 0.10	0.04	6	11 – 143	42.0	8.8 – 9.8	9.4
Gray Basalt	5	<0.01 – 0.02	0.02	4	16 - 84	36.6	8.9 – 9.6	9.1

(1) Units of tons of calcium carbonate equivalent per thousand tons of material

As discussed below in the methods section, the geostatistical analysis relies on computing the differences between sample values for unique data pairs over a range of point spacings. Only the Soudan Iron Formation and dacite have sufficient data for this type of analysis. Data from the mafic volcanics, metadiabase, and gray basalt were not used.

For this analysis, the detection limit value of 0.01% was assigned to the sulfur non-detect samples. The utilization of the detection limit (rather than omitting the non-detects or employing a fractional simple substitution method) is based on guidance from the ITRC and Helsel (ITRC, 2013; Helsel, 2012). The 2013 ITRC document Groundwater Statistics and Monitoring Compliance notes that "if the goal is to compute summary statistics such as the mean or variance…it may be inappropriate to impute the censoring limit (or some fraction of this limit) to nondetects in statistical formulas because the substitution method distorts the data (ITRC, 2013). Helsel furthermore states that "the process of substituting a fraction of the reporting limits has repeatedly been shown to produce poor results in simulation studies…substitution of a fraction of the reporting limit for censored observations should rarely be considered acceptable in a quantitative analysis (Helsel, 2012). However, the ITRC document notes, "When the nondetect proportion is quite low, statistical results based on using simple substitution are not likely to vary substantially from other methods."

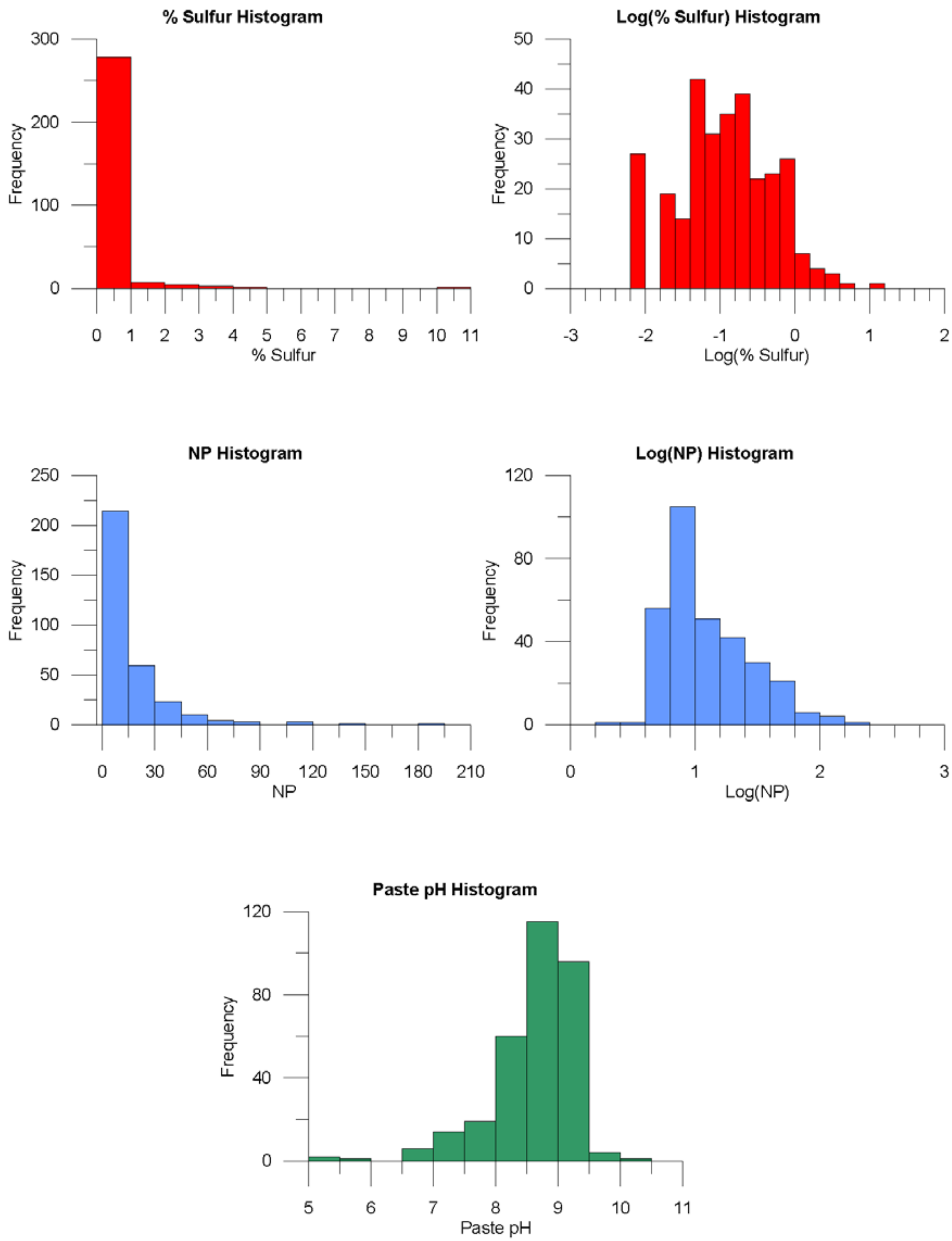


Figure 3 – Soudan Iron Formation Histograms

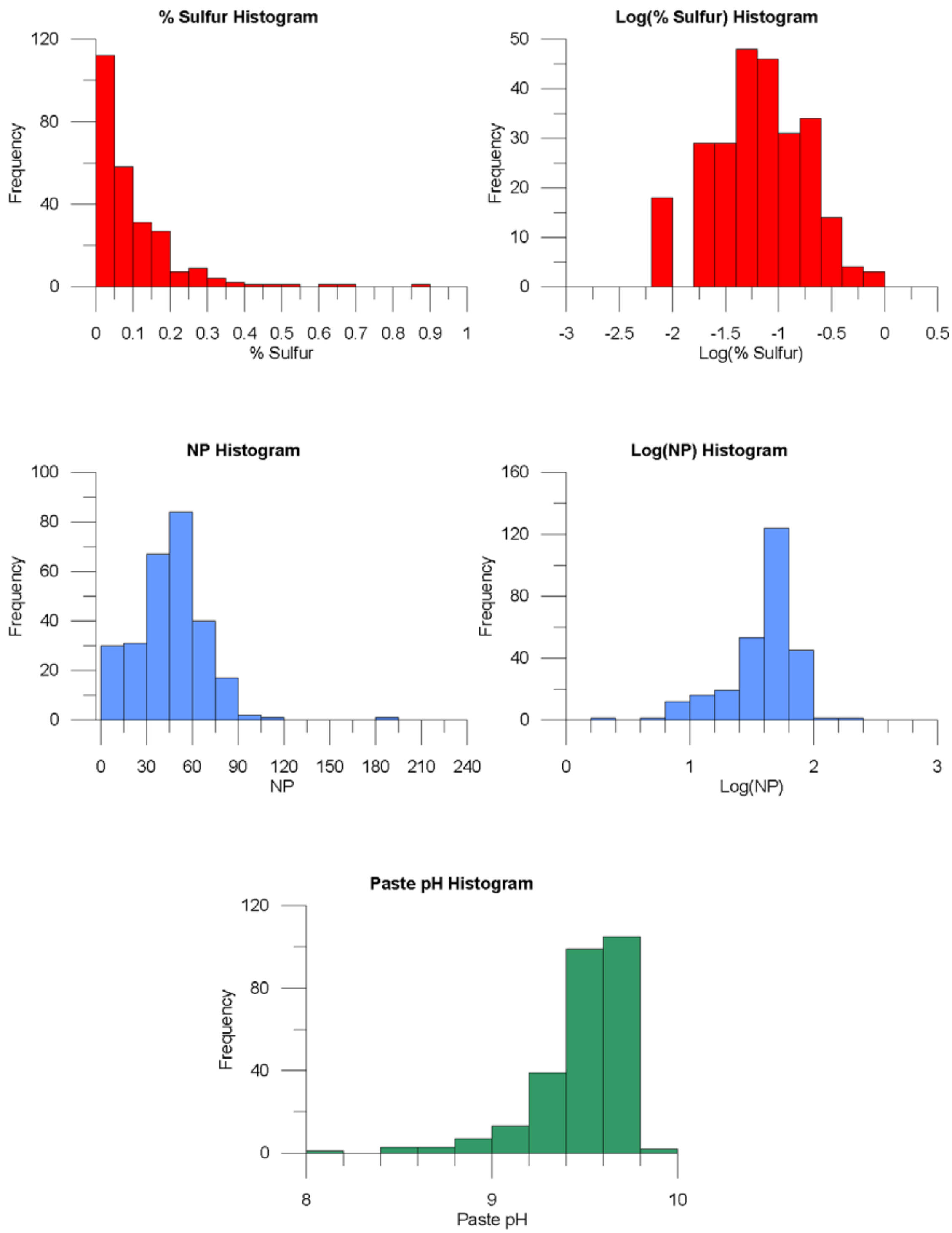


Figure 4 – Dacite Histograms

Figures 3 and 4 above show histograms of the data for the Soudan Iron Formation and Dacite, respectively. Geostatistical analyses tend to work best when the data are at least approximately normally distributed. As shown on Figures 3 and 4, the histograms for percent sulfur and neutralization potential were both positively skewed. Positively skewed distributions are commonly seen in environmental datasets, especially for parameters with values that range over orders of magnitude (e.g., concentrations, hydraulic conductivity). More symmetric distributions were achieved for these parameters by applying a logarithmic transformation to the data. The log-transformed data were used in the geostatistical analyses for percent sulfur and neutralization potential.

The data were also evaluated for the presence of trends. In geostatistical nomenclature, a trend is a systematic large-scale variation in space. Because geostatistics assumes that all spatial variability is random, a trend must be filtered from the data before proceeding with the analysis. Figures 5 and 6 show plots of each parameter versus x, y, and z coordinates for the Soudan Iron Formation and dacite, respectively. No significant trends were noted, so no filtering was applied to the datasets.

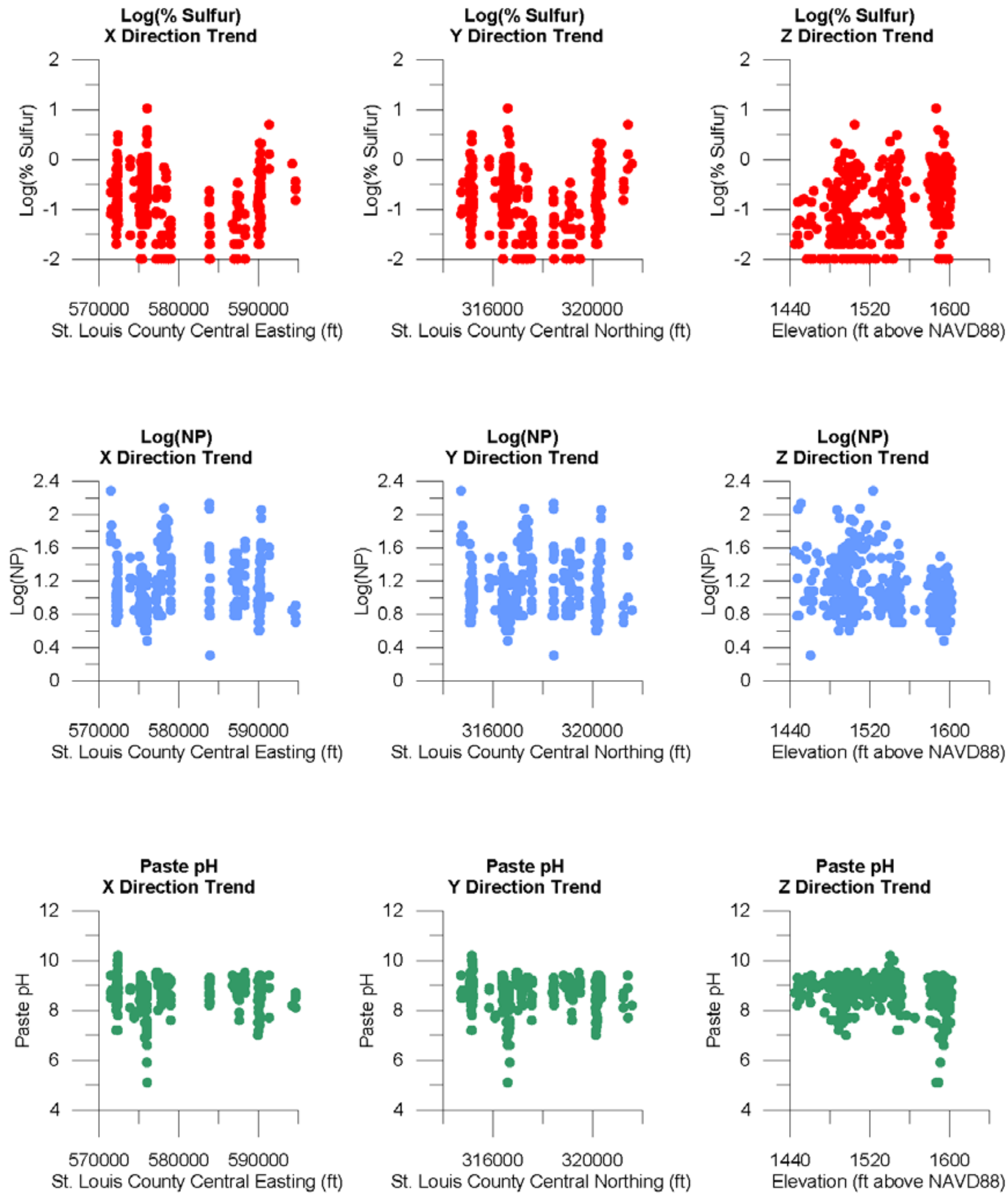


Figure 5 – Soudan Iron Formation Trend Evaluation

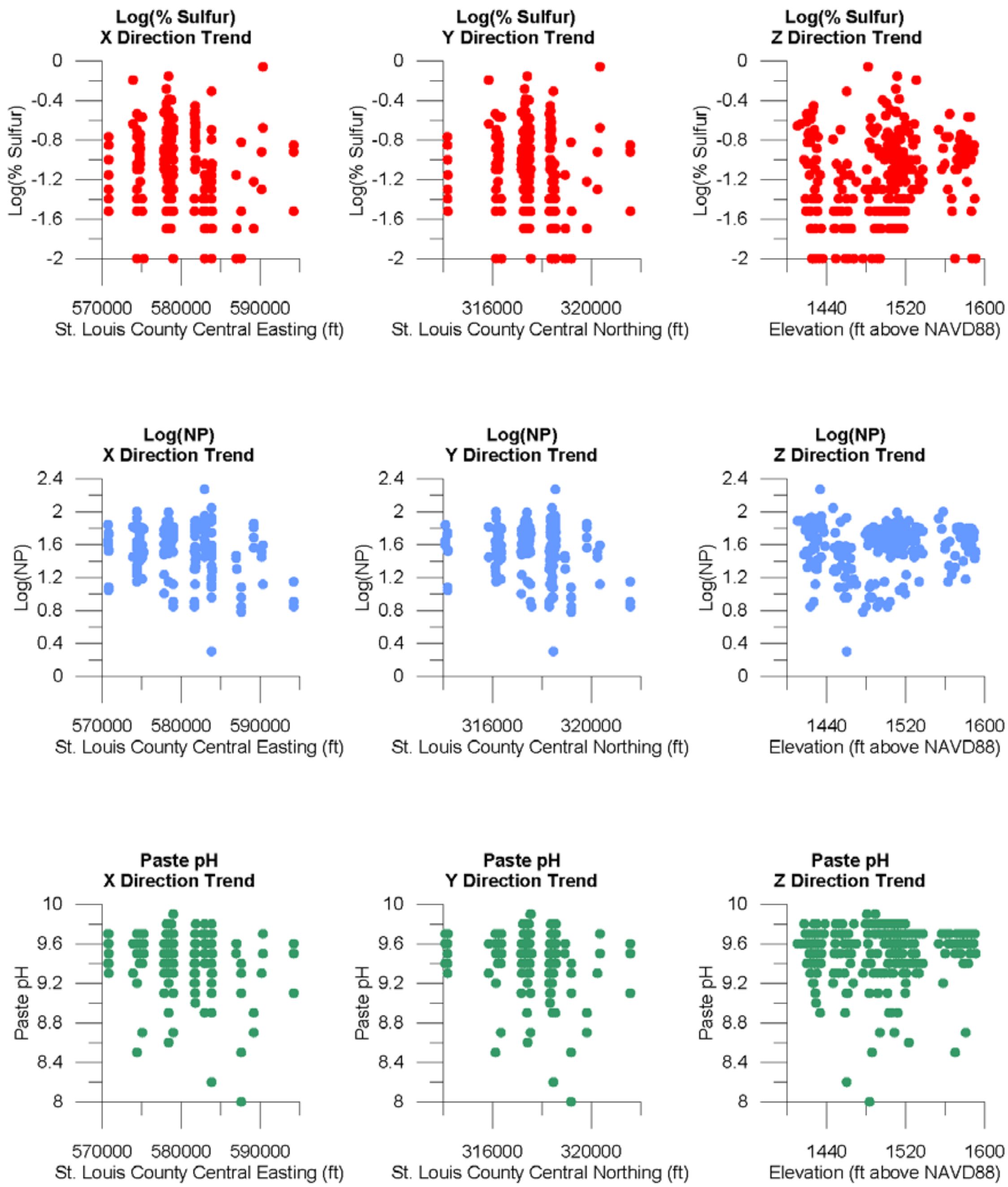


Figure 6 – Dacite Trend Evaluation

Geostatistical Analysis: Sample Spacing Analysis – Downhole

To assess optimal downhole sample spacing within a given boring, variograms were constructed for data pairs oriented along an azimuth angle of 160 degrees (+/- 5 degrees) clockwise from north and a dip angle of 45 degrees (+/- 5 degrees) below horizontal. This orientation describes 61% (80 of 131) of the borings; the remaining data were not used. Experimental variograms were constructed for a range of bin spacings; a bin spacing of 3 feet was chosen for the final analysis. The 3-foot spacing was determined to strike a good balance between an overly noisy plot (bin spacing too small) and an overly smoothed plot (bin spacing too large).

The downhole variogram fits are shown below on Figures 7-12. The number labels on the experimental variogram points denote the number of data pairs used to compute each variogram point; the points with higher numbers received more weight in the model fitting. The shapes of the experimental variograms appeared to most closely match the exponential variogram model. Because the exponential variogram model asymptotically approaches the sill value (i.e., it never completely flattens out like the conceptual diagram shown on Figure 1), the range of this variogram model is defined as the distance at which the model reaches 95% of the sill value.

As shown on Figures 11 and 12, the experimental variograms for the dacite log(NP) and paste pH did not appear to exhibit spatial correlation; variability generally decreased with increasing point spacing instead of increasing as expected. Therefore, no variogram model fits were attempted for these parameters.

Table 2 below summarizes the estimated variogram ranges for the downhole variograms.

Table 2 Downhole Variogram Range Summary

Material Type	Correlation Scales (Variogram Ranges) (feet)		
	% Sulfur	Neutralization Potential	Paste pH
Soudan Iron Formation	15	40	19
Dacite	21	-	-

As discussed above in the Methods section, a conservative rule-of-thumb is to use half of the variogram range as the optimal sample spacing. Using the smallest variogram range for each material from Table 2 and rounding up to the nearest foot, this analysis suggests a downhole sample spacing of approximately 8 feet for the Soudan Iron Formation and 11 feet for the dacite.

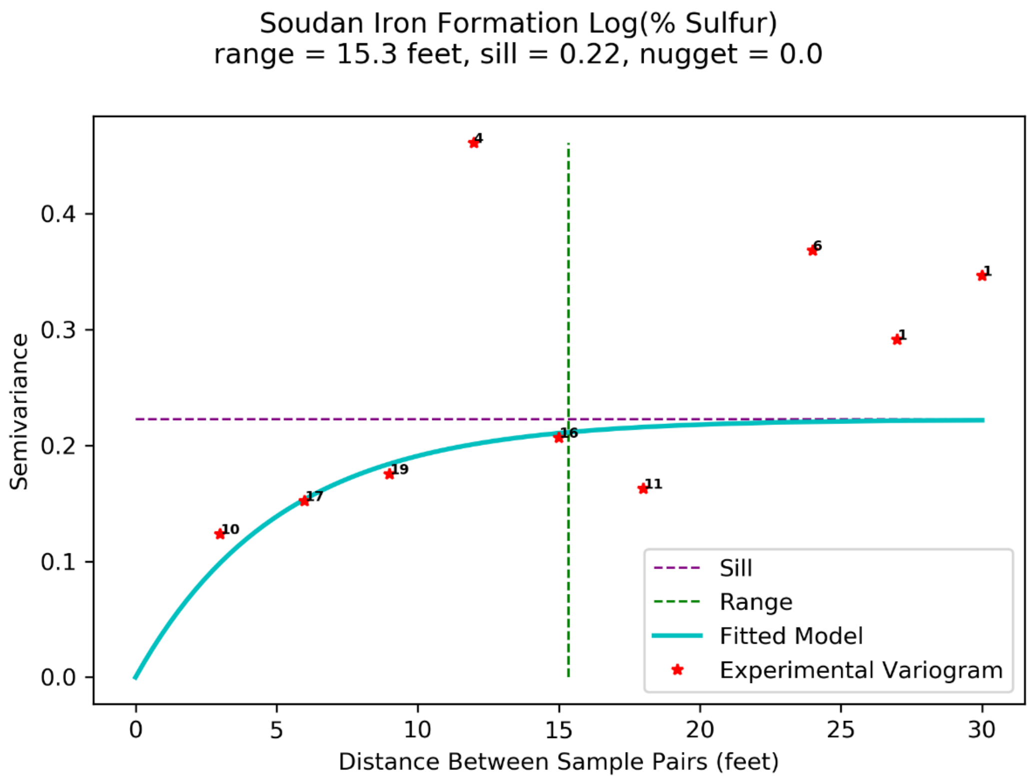


Figure 7 – Downhole Variograms, Soudan Iron Formation, Log(% Sulfur)

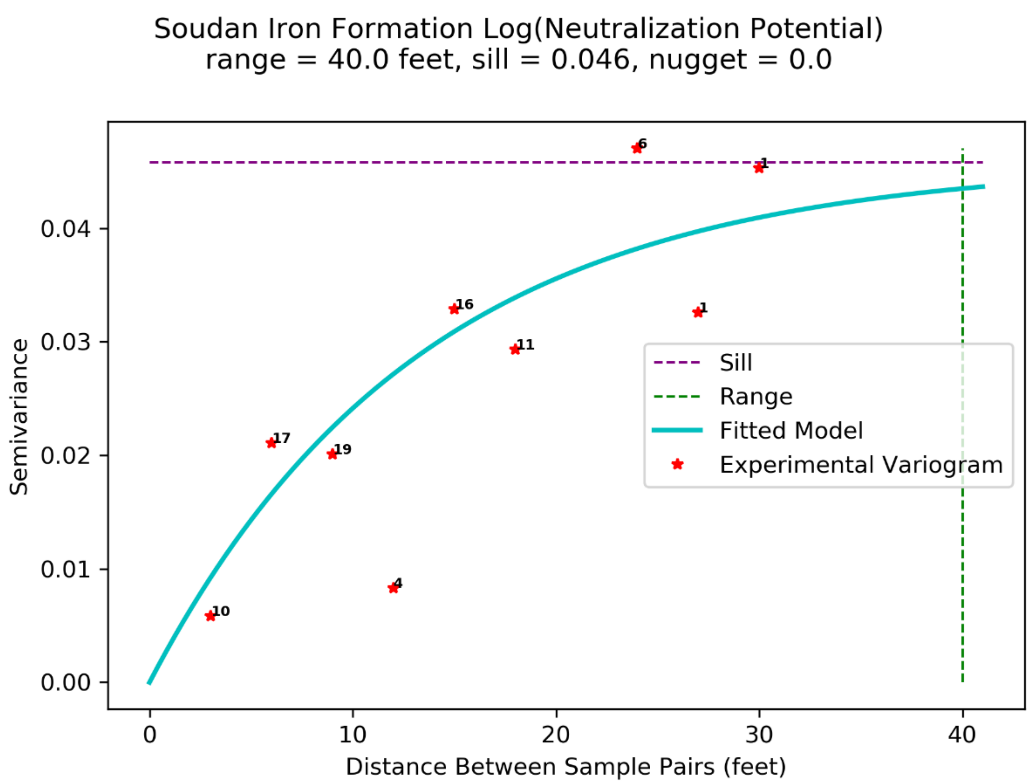


Figure 8 – Downhole Variograms, Soudan Iron Formation, Log(Neutralization Potential)

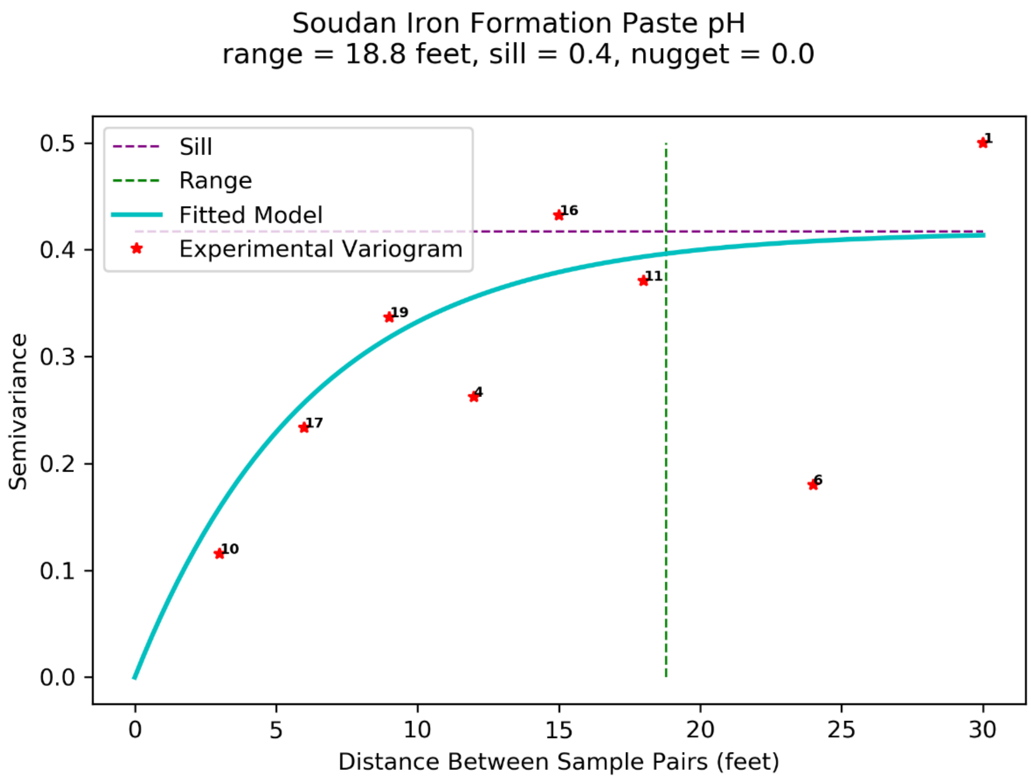


Figure 9 – Downhole Variograms, Soudan Iron Formation, paste pH

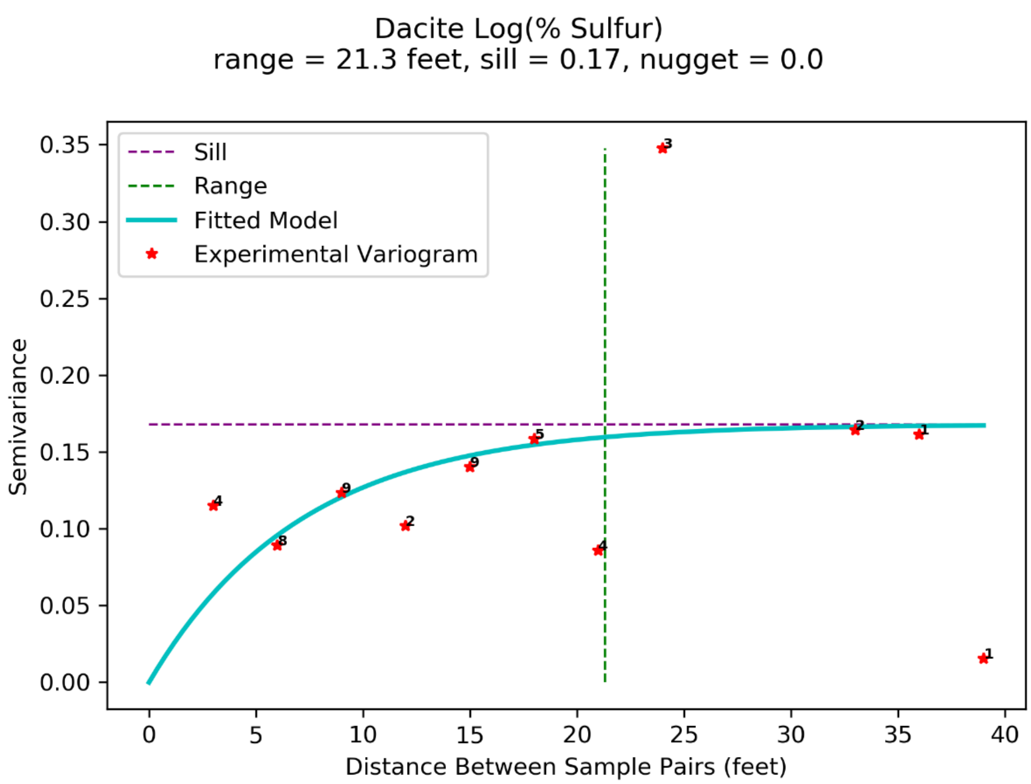


Figure 10 – Downhole Variograms, Dacite, Log(% Sulfur)

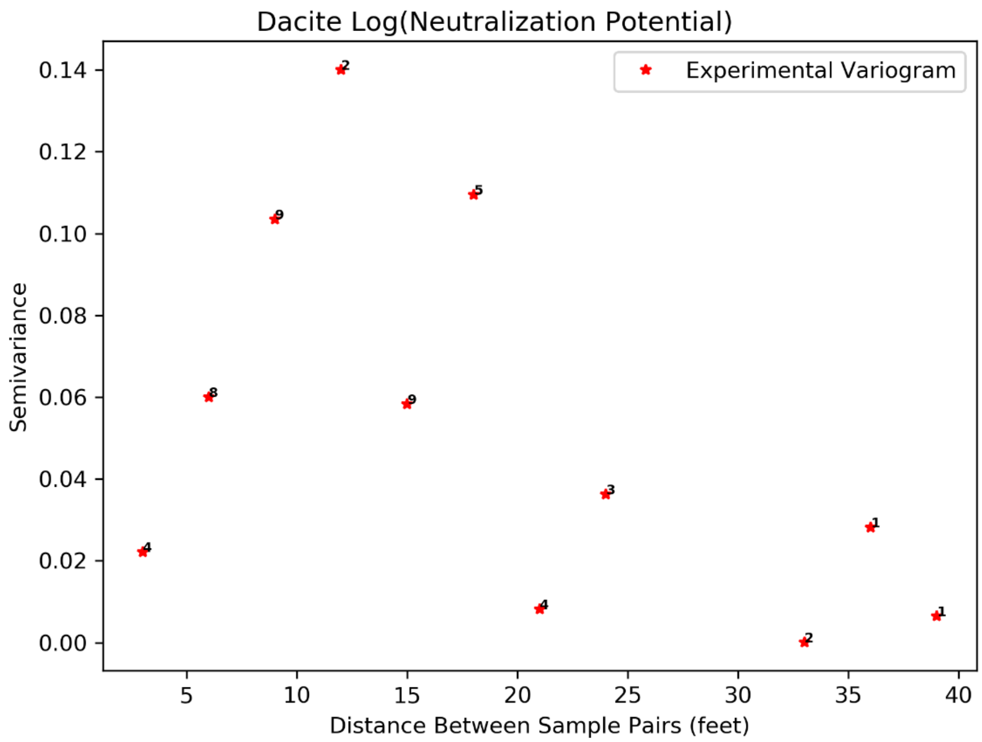


Figure 11 – Downhole Variogram, Dacite, Log(Neutralization Potential)

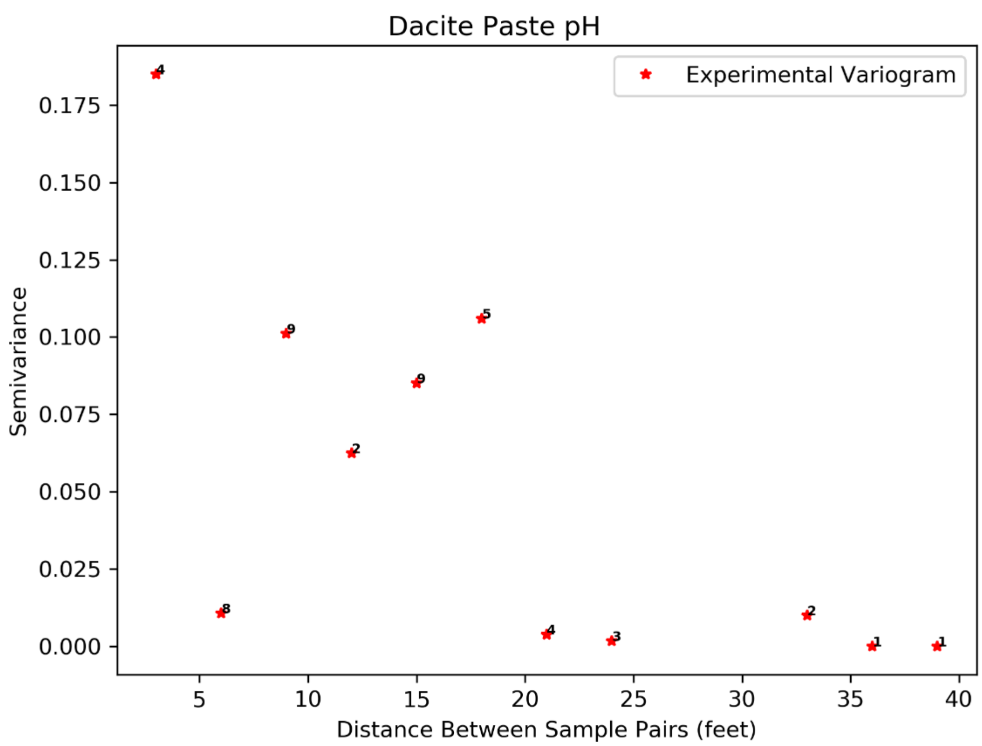


Figure 12 – Downhole Variogram, Dacite, paste pH

Geostatistical Analysis: Sample Spacing Analysis – Along Alignment

To assess optimal sample spacing along a roadway alignment, variograms were constructed for data pairs oriented along an azimuth angle of 70 degrees (+/- 10 degrees) clockwise from north. This orientation is perpendicular to the 160-degree azimuth used for the downhole analysis; the intent of the alignment analysis is to compare pairs of data points at different stations that are at similar elevations and offsets from the centerline.

Figure 13 below shows an experimental variogram calculated using Soudan Iron Formation log(%S) data from along the entire alignment.

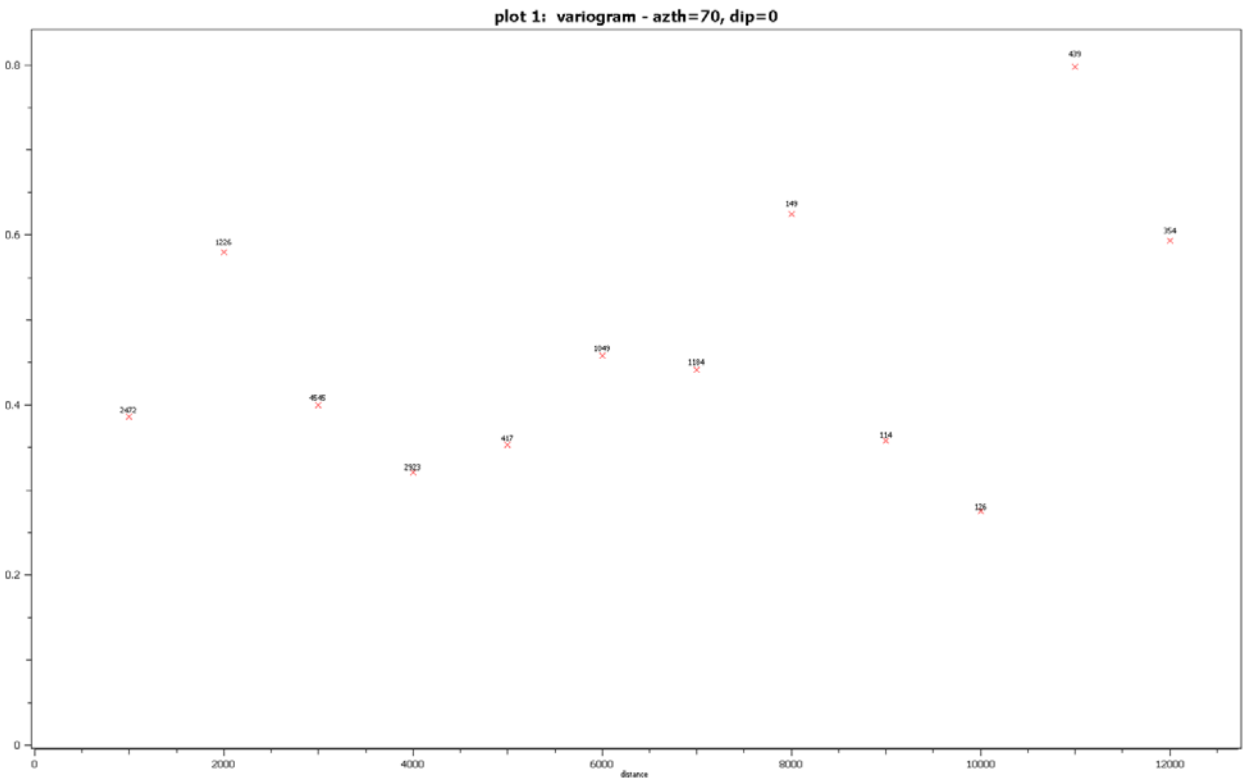
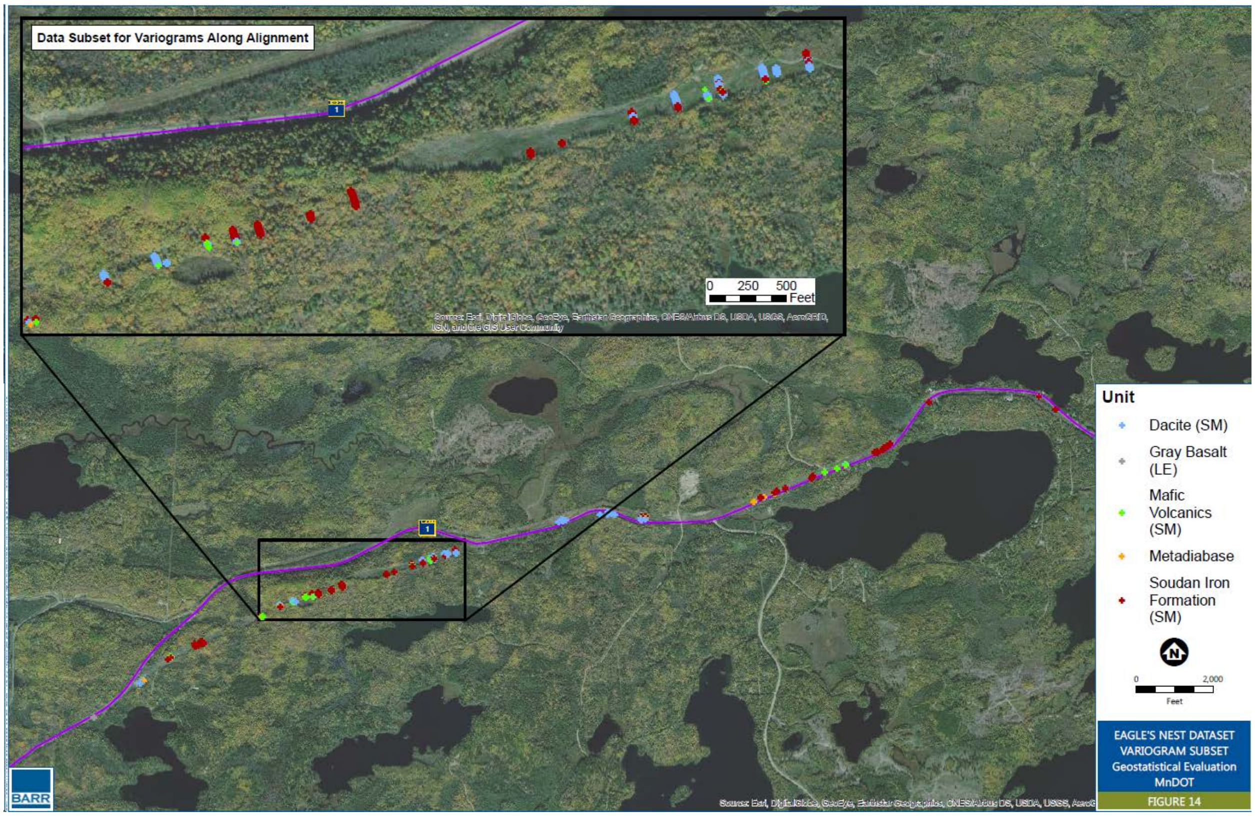


Figure 13 – Along Alignment Variogram, Soudan Iron Formation, log(%S), All Data

The points on Figure 13 don't follow any of the theoretical variogram models shown on Figure 2 and also appear to show periodic fluctuations akin to a sine wave. This periodic behavior is known as the "hole effect" and may be related to the uneven distribution of points into clumps along the alignment (see Figure 14) and/or larger-scale variability in the rock formations. Due to these effects, a smaller subset of the dataset (shown on Figure 14) was used for the analysis parallel to the alignment.



The parallel to alignment variograms are shown below on Figures 15-20. The maximum distance between samples in the subset is approximately 5,400 feet. The ITRC guidance lists a rule of thumb that the maximum spacing used in the variogram should not exceed half of the maximum sample spacing (i.e., 2,700 feet in this case). Horizontal axis ranges of 1,700 feet and 1,200 feet were used for the Soudan Iron Formation and dacite, respectively.

In general, less spatial correlation was observed in the experimental variograms parallel to the alignment than was observed in the downhole analysis. Correspondingly, the variogram model fits were not as good for the alignment analysis. Only the log(NP) experimental variograms showed enough spatial correlation to attempt a variogram model fit. Table 3 below summarizes the estimated variogram ranges for the along alignment variograms.

Table 3 Along Alignment Variogram Range Summary

Material Type	Correlation Scales (Variogram Ranges) (feet)		
	% Sulfur	Neutralization Potential	Paste pH
Soudan Iron Formation	-	655	-
Dacite	-	920	-

Using half of single variogram range for the Soudan Iron Formation from Table 3 and rounding to the nearest 50 feet gives an optimal sample spacing parallel to the 36-foot-wide alignment of approximately 350 feet for this material. The same calculation on the single result for the dacite would suggest a 450-foot spacing.

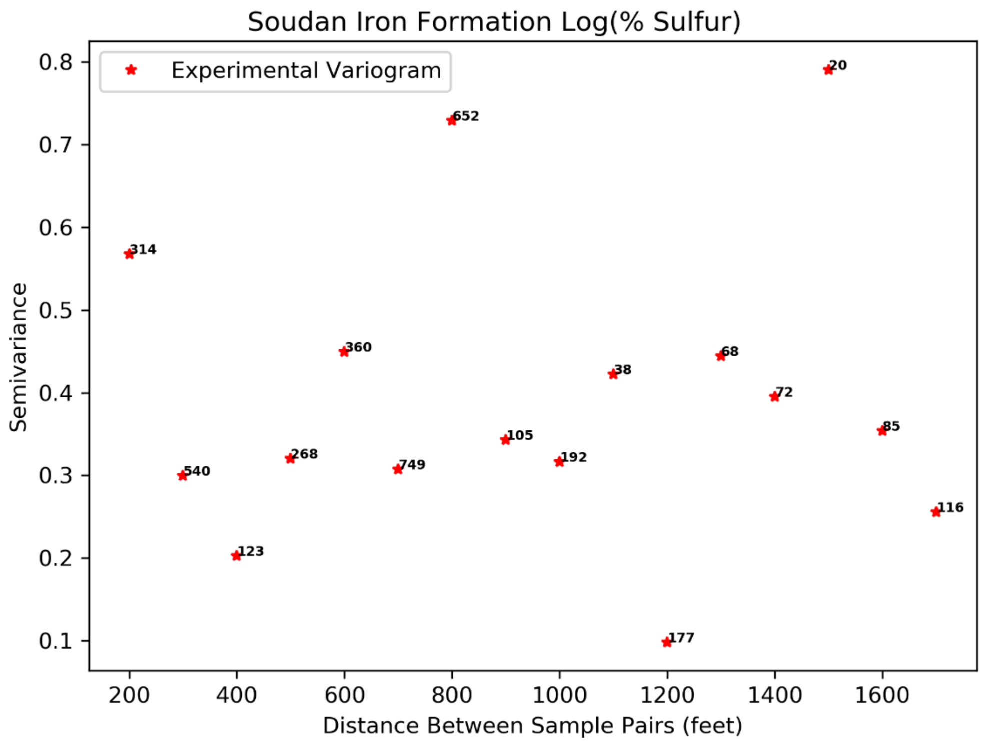


Figure 15 – Along Alignment Variograms, Soudan Iron Formation, Log(% Sulfur), Data Subset

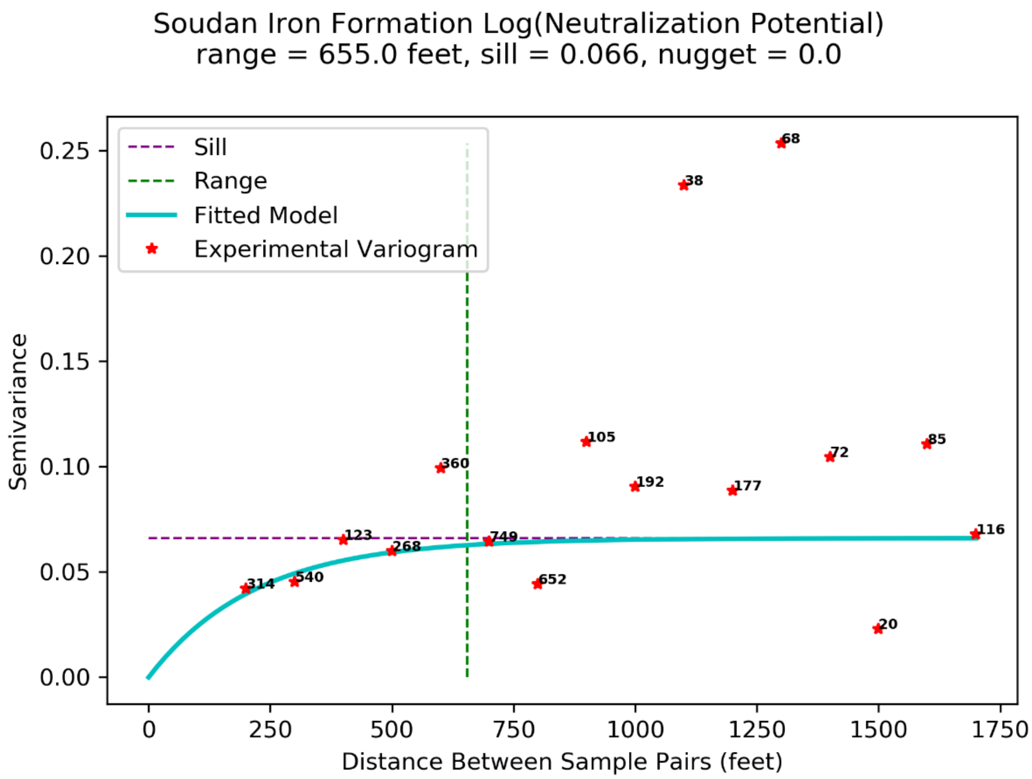


Figure 16 – Along Alignment Variograms, Soudan Iron Formation, Log(Neutralization Potential), Data Subset

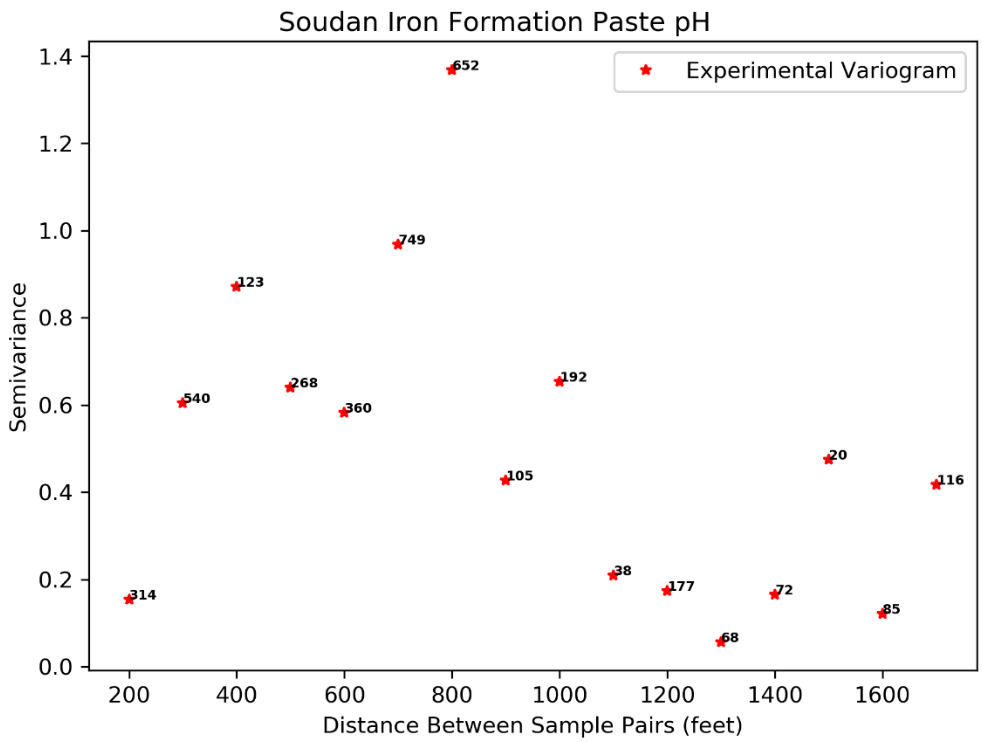


Figure 17 – Along Alignment Variograms, Soudan Iron Formation, paste pH, Data Subset

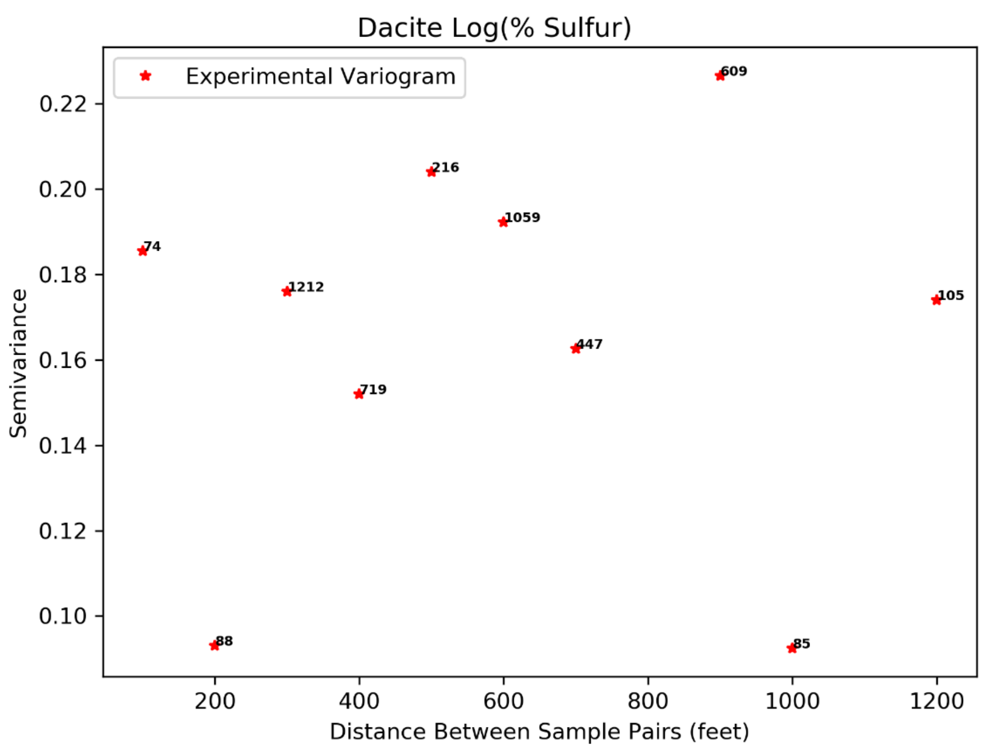


Figure 18 – Along Alignment Variograms, Dacite, Log(% Sulfur), Data Subset

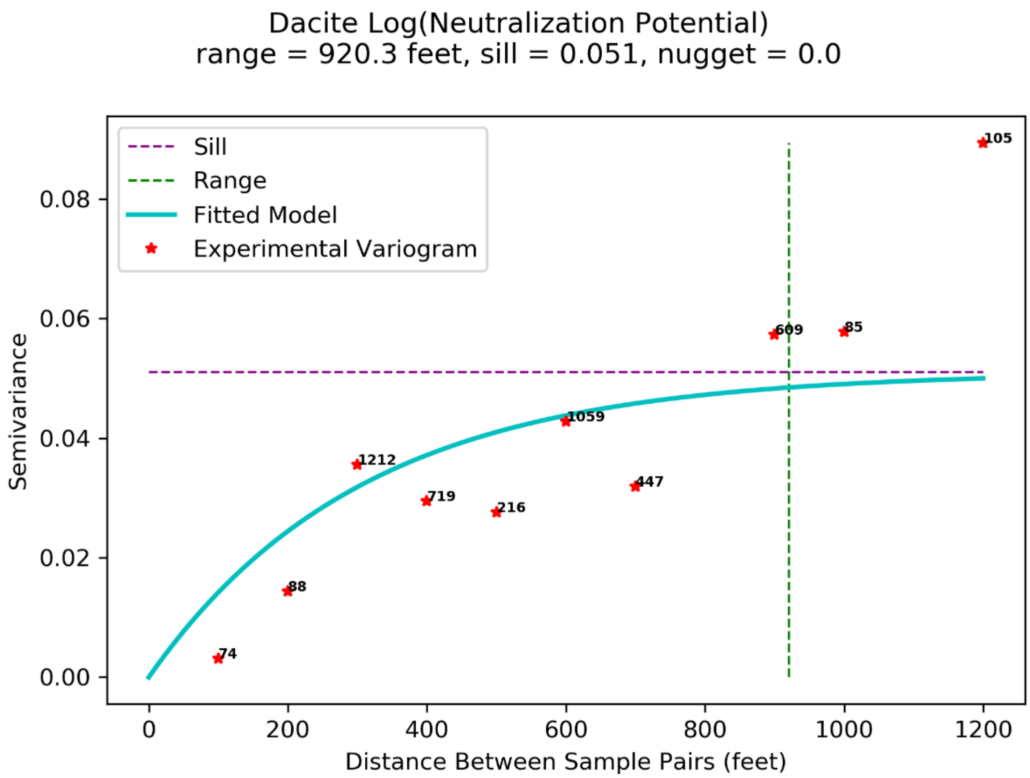


Figure 19 – Along Alignment Variogram, Dacite, Log(% Neutralization Potential), Data Subset

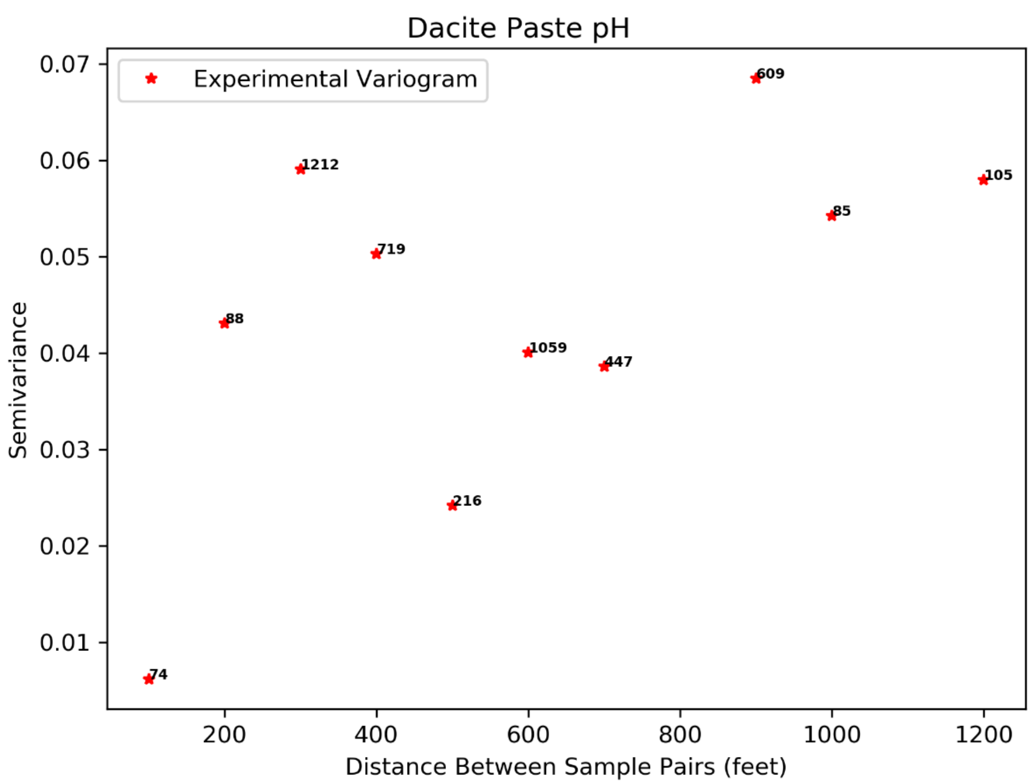


Figure 20 – Along Alignment Variogram, Dacite, paste pH, Data Subset

Geostatistical Analysis: Summary

The results of the analysis suggest an optimal downhole sample spacing of approximately 8 feet in the Soudan Iron Formation and 11 feet in the dacite. Parallel to the 36-foot-wide road alignment, the results of the analysis suggest an optimal sample spacing of approximately 350 feet in the Soudan Iron Formation and 450 feet in the dacite. The larger sample spacing in the dacite is consistent with the lower sulfur content of the dacite compared to the Soudan Iron Formation. The degree of spatial correlation observed in the parallel to alignment analysis was far less than that observed in the downhole analysis; therefore, less confidence should be applied to the results parallel to the alignment. These numbers do not define a sampling plan by themselves but provide useful information to be considered when designing a sampling plan.

Sample Number Analysis: Introduction

This portion of the memorandum describes the methods and results of the sample number analysis of the combined 2015 Eagle's Nest drilling (Heine et al., 2017) and, in contrast to the geostatistical evaluation, the 2017 construction observation datasets. This analysis was conducted for the purpose of estimating required numbers of samples per excavated volume to adequately characterize the sulfur content of potentially acid-generating rock units in Minnesota.

Based on the number of available data points, only the Soudan Iron Formation, dacite, and mafic volcanic rock types were evaluated. The results of the analysis suggest that for the Eagle's Nest project, the mean sulfur contents of the Soudan Iron Formation and the dacite could have been adequately determined with approximately 20% and 30% fewer samples, respectively, than were actually collected. A similar analysis was also conducted for the mafic volcanics, but the results were inconclusive. For future projects, the results of this analysis recommend collecting a sample for every 140 cubic yards of Soudan Iron Formation and for every 400 cubic yards of dacite to be excavated.

This portion of the memorandum is organized into the following sections: presentation of methods, dataset description, and a summary of results.

Sample Number Analysis: Methods

This analysis used a similar methodology to that described in Garvie and Kentwell (2017). The basic idea is to compute a mean sulfur content using all of the available data and then evaluate how many samples were actually necessary to approximate the true mean. Garvie and Kentwell used the arithmetic mean; the geometric mean was used for this analysis because the Eagle's Nest sulfur data are not normally distributed.

The analysis procedure is described step-by-step as follows:

1. Compute the geometric mean of all available data for a given rock type
2. Reorder the full dataset using a random number generator (i.e., assign a random number to each data point and then sort the dataset by increasing random number)
3. Compute the geometric mean for subsets of the reordered dataset (e.g., first 10 points, first 20 points, first 30 points, etc.)
4. Repeat steps 2 and 3 over multiple iterations until a "successful" geometric mean is achieved.

5. Process the results of step 3. For each number of samples used in the mean calculations, determine how many of the calculated means are within a tolerance of the true mean.

This analysis used 10,000 realizations (i.e., number of times steps 2 and 3 were repeated) for the Soudan Iron Formation and the dacite. A total of 3,500 realizations were used for the mafic volcanics analysis; this number was chosen because the number of unique permutations of 2 samples chosen from a set of 63 samples is only 3,906. A mean calculation was considered "successful" if the calculated mean from a subset of the data was within +/- 10% of the true mean. The +/- 10% tolerance is arbitrary but is based on professional judgment and is considered conservative.

Sample Number Analysis: Dataset

The combined pre-construction and construction observation Eagle's Nest dataset consists of 901 individual samples from 11 different rock types. Table 4 below summarizes the sample data by rock type. As with the geostatistical analysis, the detection limit of 0.01 was used for the pre-construction sulfur samples; for the purposes of the mean calculations, this value was assigned to the non-detect samples. Construction observation samples (n=28) were detected below the detection limits for pre-construction sampling analyses; however, no non-detected values were reported in this dataset (i.e., all data in this dataset had quantifiable results).

Table 4 Parameter Values by Material Type

Material Type	Sample Count	Excavated Volume (yd^3)	Weight % Sulfur		
			Range	Geometric Mean	Non-detect Count
Soudan Iron Formation	408	48,196	0.0014 – 10.6	0.095	24
Dacite	374	103,068	0.020 – 2.64	0.053	17
Mafic Volcanics	63	5,526	<0.01 – 0.30	0.022	22
Metadiabase	24	2,467	<0.01 – 0.10	0.020	6
Dacite/Soudan Iron Formation	13	6,658	0.0031 – 0.07	0.016	0
Gray Basalt	10	1,481	0.0026 – 0.15	0.014	4
Metadiabase/Dacite	4	694	0.0089 – 0.048	0.022	0
Altered Unit	2	1,179	0.0058 – 0.16	0.030	0
Chert	1	109	0.15	-	0
Soudan Iron Formation/Altered Unit	1	1,133	0.093	-	0
Overburden	1	162	0.020	-	0

Excavated volumes were reported by rock cut section during construction. The excavated volumes by rock type shown in Table 4 above were approximated by first summing the sampled thicknesses of each rock type at each rock cut section and then using a thickness-weighted average to apportion the total excavated volume for the rock cut section to each rock type. A table of these computations is included as Appendix A.

Sample Number Analysis: Results

Figures 21-23 and the accompanying Tables 5-7 below summarize the results of the sample number analysis for the Soudan Iron Formation, dacite, and mafic volcanics, respectively.

The results of the Soudan Iron Formation and dacite analyses suggest that the geometric mean sulfur contents of these two rock types could have been adequately approximated with fewer samples than were actually collected as part of the Eagle's Nest project. The geometric mean sulfur content of the Soudan Iron Formation was calculated within the +/-10% tolerance for 99% of the realizations using 329 samples in the mean calculation, a 19% reduction from the actual 408 samples collected. For the dacite, the geometric mean sulfur content was calculated within the +/-10% tolerance for 99% of the realizations using 244 samples in the mean calculation, a 35% reduction from the actual 374 samples collected. To generalize these results for use in determining sampling requirements for other sites with similar rock types, Tables 5 and 6 also include estimates of the maximum volume that can be excavated per one sample collected. For the 99% confidence level and rounded down to the nearest 10 cubic yards, these numbers are 140 cubic yards of Soudan Iron Formation per sample and 420 cubic yards of dacite per sample. It makes sense that the maximum volume per sample is higher (i.e., more samples required) for the Soudan Iron Formation than the dacite because the sulfur content of the former is both higher and more variable than the latter.

Note that the use of the 99% confidence level in the above discussion of the results is conservative and based on professional judgment. Tables 5 and 6 include results for lower confidence levels that could be used if a lower confidence level is deemed appropriate.

As shown on Figure 23, the success rate levels off much closer to the actual number of samples for the mafic volcanics than it did for the Soudan Iron Formation and dacite. One might conclude from this result that the mafic volcanics were undersampled; however, there may not have been enough available data for this type of analysis. In addition, the relatively high percentage of non-detect samples (22 of 63, or 35%) may also have affected the results.

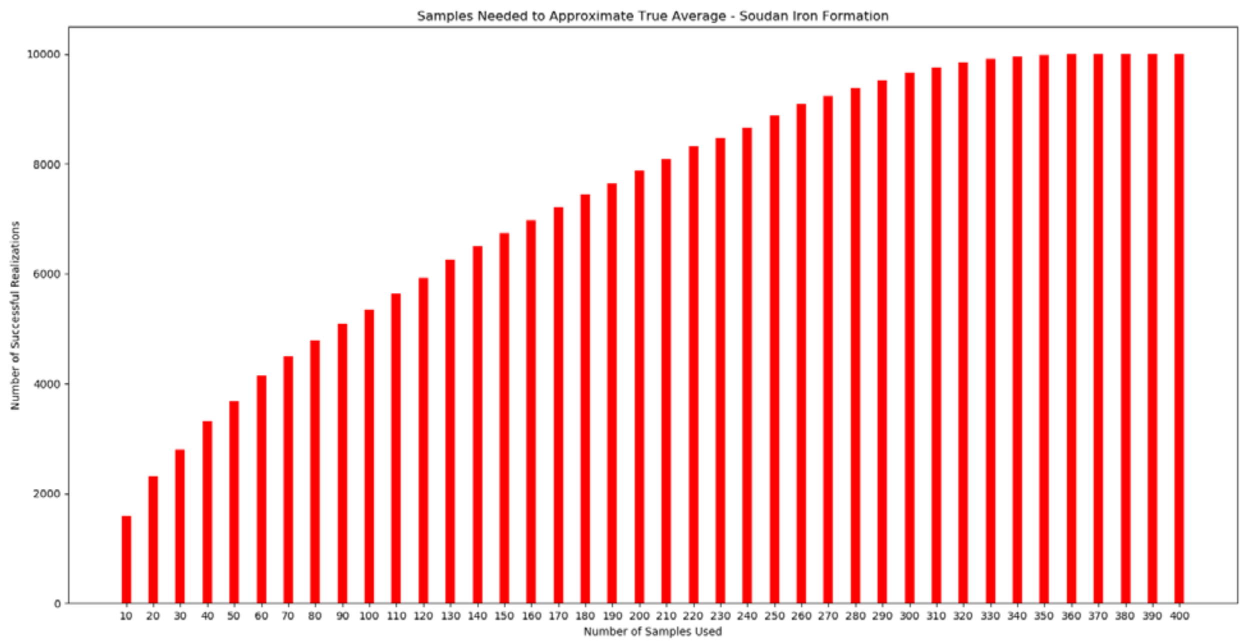


Figure 21 Successful Realizations by Sampling Level – Soudan Iron Formation

Table 5 Realization Success Rates and Volumes per Sample – Soudan Iron Formation

Soudan Iron Formation Actual number of samples = 408 Estimated excavated volume = 48,196 yd^3 Actual excavated volume per sample = 118 yd^3			
Success Rate	**Number of Samples**	**Volume per Sample (yd^3)**	**% Sampling Reduction from Actual**
25%	24	2,008	94
50%	87	554	79
75%	183	263	55
90%	256	188	37
95%	289	167	29
99%	329	146	19

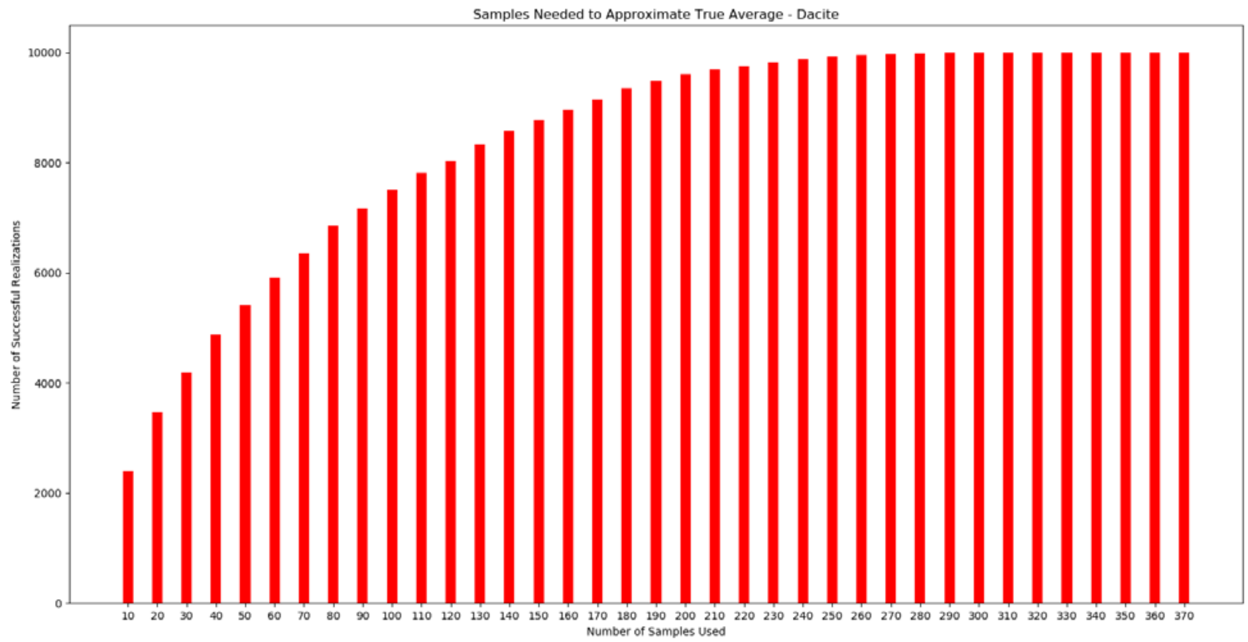


Figure 22 Successful Realizations by Sampling Level – Dacite

Table 6 Realization Success Rates and Volumes per Sample – Dacite

Dacite Actual number of samples = 374 Estimated excavated volume = 103,068 yd³ Actual excavated volume per sample = 276 yd³			
Success Rate	**Number of Samples**	**Volume per Sample (yd^3)**	**% Sampling Reduction from Actual**
25%	11	9,370	97
50%	43	2,397	89
75%	100	1,031	73
90%	163	632	56
95%	191	540	49
99%	244	422	35

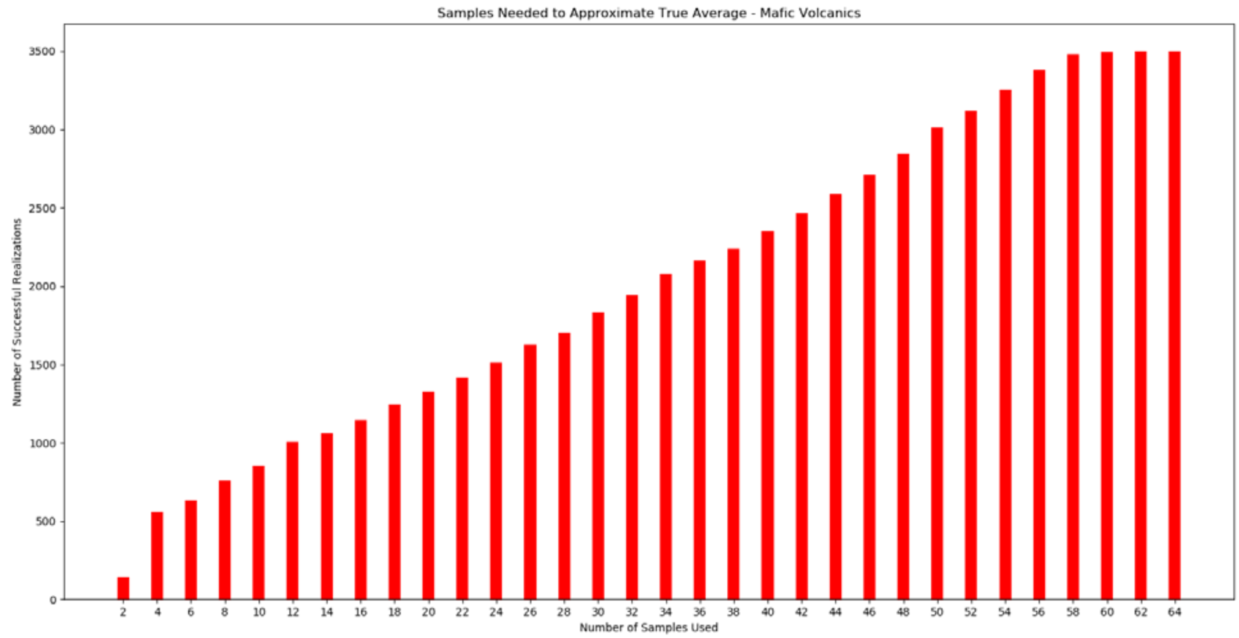


Figure 23 Successful Realizations by Sampling Level – Mafic Volcanics

Table 7 Realization Success Rates and Volumes per Sample – Mafic Volcanics

Mafic Volcanics Actual number of samples = 63 Estimated excavated volume = 5,526 yd³ Actual excavated volume per sample = 88 yd³			
Success Rate	**Number of Samples**	**Volume per Sample (yd³)**	**% Sampling Reduction from Actual**
25%	11	502	83
50%	29	191	54
75%	45	123	29
90%	53	104	16
95%	56	99	11
99%	58	95	8

Sample Number Analysis: Summary

The results of the analysis suggest that for the Eagle's Nest project, the mean sulfur contents of the Soudan Iron Formation and the dacite could have been adequately determined with approximately 20% and 35% fewer samples, respectively, than were actually collected. A similar analysis was also conducted for the mafic volcanics, but the results were inconclusive. For future projects, the results of this analysis recommend collecting a sample for every 140 cubic yards of Soudan Iron Formation and for every 420 cubic yards of dacite to be excavated. These numbers are conservative and based on a 99% confidence level.

Comparative Summary

The results of the two different evaluations provide somewhat dissimilar results through different approaches. For example, the geostatistical analysis suggests one sample per 3,700 cubic yards of Soudan Iron Formation for a 36-foot-wide 2-lane highway and shoulder (350 feet parallel to alignment × 36 feet perpendicular to alignment × 8 feet vertically / 27 cubic feet per cubic yard), which is considerably less frequent than the one sample per 140 cubic yards of Soudan Iron Formation from the sample number analysis. However, recall that the geostatistical analysis parallel to the roadway was conducted on a limited subset of the data due to the uneven distribution of points into clumps along the alignment and/or larger-scale variability in the rock formations. The sample number analysis, meanwhile, used the entire dataset and accounts for the variability in the dataset that shows no spatial correlation.

The key assumptions of performing these analyses are useful in interpretation of this sampling frequency comparison. In particular, these results are based on samples that were collected from specific rock types in a specific location. Sample collection from other geologic units or in different locations may exhibit different degrees of variability in the results. For the rocks considered in this study, the degree of spatial correlation was marginal at best, particularly parallel to the roadway alignment. Therefore, the sample number analysis, which accounts for all variability present in the dataset, likely provides a more robust estimate of required sampling frequency than the geostatistical analysis, which considers spatially-correlated variability only.

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Rock Cut	Rock Cut Section	Total Excavated Volume (yd^3)	Material Encountered	Number of Samples Collected	Total Thickness of Samples Collected (feet)	Percent of Total Thickness	Volume of Material (yd^3)
A	A1	0	--	--	--	--	--
	A2	375	Gray Basalt (LE)	3	14.5	100.0%	375
B	B1	1370	Altered Unit	1	6.3	14.5%	199
			Dacite (SM)	3	15.5	35.7%	489
			Gray Basalt (LE)	3	15.2	35.0%	480
			Soudan Iron Formation (SM)	1	6.4	14.7%	202
	B2	1330	Dacite (SM)	8	30.7	52.0%	692
			Gray Basalt (LE)	4	27.8	47.1%	626
			Metadiabase	1	0.5	0.8%	11
	B3	511	Dacite (SM)	8	42.3	95.5%	488
			Metadiabase	1	2.0	4.5%	23
C	C1	62	Mafic Volcanics (SM)	7	27.5	59.8%	37
			Soudan Iron Formation (SM)	5	18.5	40.2%	25
	C2	0	--	--	--	--	--
	C3	0	--	--	--	--	--
D	D1	22	Unknown	--	--	--	22
	D2	145	Unknown	--	--	--	145
E	E1	765	Metadiabase	1	4.0	5.4%	42
			Soudan Iron Formation (SM)	16	69.8	94.6%	724
	E2	436	Soudan Iron Formation (SM)	10	42.4	100.0%	436
	E3	558	Soudan Iron Formation (SM)	26	114.8	100.0%	558
	E4	222	Soudan Iron Formation (SM)	4	14.6	100.0%	222
F	F1	0	--	--	--	--	--
G	G1	0	Dacite (SM)	1	1.5	60.0%	0
			Soudan Iron Formation (SM)	1	1	40.0%	0
	G2	0	Dacite (SM)	1	2.5	10.2%	0
			Mafic Volcanics (SM)	3	13	53.1%	0
			Metadiabase	2	9	36.7%	0
	G3	0	Soudan Iron Formation (SM)	2	4.5	100.0%	0
H	H1	702	Dacite (SM)	12	50.5	69.5%	487
			Metadiabase	1	4.0	5.5%	39
			Metadiabase/Dacite	3	8.9	12.2%	86
			Soudan Iron Formation (SM)	3	9.3	12.8%	90
	H2	6060	Dacite (SM)	30	220.0	92.7%	5615
			Mafic Volcanics (SM)	2	5.9	2.5%	151
			Metadiabase	2	8.0	3.4%	204
			Soudan Iron Formation (SM)	1	3.5	1.5%	89
	H3	5377	Dacite (SM)	27	160.9	89.2%	4796
			Mafic Volcanics (SM)	5	19.5	10.8%	581
	H4	3347	Mafic Volcanics (SM)	7	27.0	23.1%	773
			Metadiabase	4	18.0	15.4%	515
			Soudan Iron Formation (SM)	14	72.0	61.5%	2059
	H5	1854	Dacite (SM)	3	15.5	13.2%	244
			Mafic Volcanics (SM)	2	2.0	1.7%	32
			Soudan Iron Formation (SM)	23	100.1	85.1%	1578
	H6	2005	Soudan Iron Formation (SM)	40	172.9	100.0%	2005
	H7	6182	Soudan Iron Formation (SM)	30	187.4	100.0%	6182
	H8	4873	Soudan Iron Formation (SM)	28	175.9	100.0%	4873
I	I1	91	Soudan Iron Formation (SM)	8	40.3	100.0%	91
J	J1	38	Soudan Iron Formation (SM)	4	13.0	100.0%	38
	J2	205	Unknown	--	--	--	205
	J3	7	Unknown	--	--	--	7
K	K1	364	Soudan Iron Formation (SM)	3	9.7	100.0%	364
	K2	753	Dacite (SM)	7	30.5	35.7%	269
			Mafic Volcanics (SM)	2	6.0	7.0%	53
			Soudan Iron Formation (SM)	13	49.0	57.3%	432
L	L1	2593	Dacite (SM)	7	36.0	70.3%	1822
			Metadiabase/Dacite	1	12.0	23.5%	608
			Overburden	1	3.2	6.3%	162
	L2	16731	Dacite (SM)	26	274.2	88.4%	14789
			Mafic Volcanics (SM)	1	5.0	1.6%	270
			Soudan Iron Formation (SM)	3	10.0	3.2%	539
			Soudan Iron Formation/Altered Unit	1	21.0	6.8%	1133
	L3	10446	Dacite (SM)	19	89.9	81.6%	8522
			Mafic Volcanics (SM)	4	14.3	13.0%	1356
			Soudan Iron Formation (SM)	2	6.0	5.4%	569
	L4	26745	Dacite (SM)	48	536.1	76.1%	20360
			Dacite/Soudan Iron Formation (SM)	2	48.6	6.9%	1846
			Mafic Volcanics (SM)	8	32.5	4.6%	1234
			Soudan Iron Formation (SM)	10	87.0	12.4%	3304
	L5	17807	Altered Unit	1	25.1	5.5%	980
			Dacite (SM)	38	374.5	82.1%	14618
			Soudan Iron Formation (SM)	3	56.6	12.4%	2209
	L6	3424	Dacite (SM)	12	61.6	46.9%	1605
			Soudan Iron Formation (SM)	19	69.9	53.1%	1819
M	M1	602	Dacite (SM)	5	10.4	100.0%	602
	M2	2070	Dacite (SM)	4	19.5	100.0%	2070
	M3	2131	Dacite (SM)	19	89.0	100.0%	2131
	M4	107	Dacite (SM)[1]	0	1.0	100.0%	107
N	N	17274	Dacite (SM)	39	342.9	100.0%	17274
O	O1	3043	Dacite (SM)	25	98.0	71.5%	2177
			Soudan Iron Formation (SM)	11	39.0	28.5%	866
	O2	0	Dacite (SM)	2	3.5	12.5%	0
			Mafic Volcanics (SM)	2	10	35.7%	0
			Soudan Iron Formation (SM)	5	14.5	51.8%	0
	O3	0	Dacite (SM)	3	3.75	44.1%	0
			Metadiabase	1	2	23.5%	0
			Soudan Iron Formation (SM)	1	2.75	32.4%	0
P	P1	0	--	--	--	--	--
	P2	0	--	--	--	--	--
	P3	0	--	--	--	--	--
Q	Q1	30	Mafic Volcanics (SM)	1	5.0	35.7%	11
			Soudan Iron Formation (SM)	2	9.0	64.3%	19
	Q2	1112	Dacite/Soudan Iron Formation (SM)	4	11.4	50.8%	565
			Metadiabase	3	11.0	49.2%	547
	Q3	839	Dacite (SM)	4	19.0	27.6%	232
			Metadiabase	3	15.0	21.8%	183
			Soudan Iron Formation (SM)	7	34.8	50.5%	424
	Q4	7160	Dacite (SM)	2	29.5	19.2%	1378
			Dacite/Soudan Iron Formation (SM)	3	48.2	31.4%	2251
			Metadiabase	3	13.5	8.8%	631
			Soudan Iron Formation (SM)	10	62.1	40.5%	2901
	Q5	4833	Dacite (SM)	2	36.6	20.7%	1001
			Dacite/Soudan Iron Formation (SM)	3	65.6	37.1%	1794
			Metadiabase	2	10.0	5.7%	273
			Soudan Iron Formation (SM)	10	64.6	36.5%	1765
	Q6	316	Dacite (SM)	5	21.0	46.7%	148
			Mafic Volcanics (SM)	2	7.0	15.6%	49
			Soudan Iron Formation (SM)	5	17.0	37.8%	120
R	R1	648	Dacite (SM)	1	3.8	11.4%	74
			Mafic Volcanics (SM)	1	4.8	14.5%	94
			Soudan Iron Formation (SM)	6	24.5	74.0%	480
	R2	1584	Dacite (SM)	1	8.8	9.9%	157
			Dacite/Soudan Iron Formation (SM)	1	11.3	12.8%	202
			Mafic Volcanics (SM)	6	26.0	29.4%	465
			Soudan Iron Formation (SM)	7	42.5	48.0%	760
	R3	0	Mafic Volcanics (SM)	5	21.0	100.0%	0
	R4	1258	Dacite (SM)	5	18.9	27.6%	348
			Mafic Volcanics (SM)	5	22.9	33.5%	421
			Soudan Iron Formation (SM)	4	26.6	38.9%	489
	R5	33	Unknown	--	--	--	33
	R6	0	--	--	--	--	--
S	S1	0	--	--	--	--	--
	S2	616	Soudan Iron Formation (SM)	15	62.6	100.0%	616
	S3	3790	Soudan Iron Formation (SM)	11	113.7	100.0%	3790
	S4	882	Dacite (SM)	2	7.3	15.1%	133
			Soudan Iron Formation (SM)	10	41.0	84.9%	749
	S5	2570	Soudan Iron Formation (SM)	9	42.7	100.0%	2570
	S6	3704	Dacite (SM)	2	8.0	6.1%	227
			Soudan Iron Formation (SM)	14	122.8	93.9%	3477
	S7	0	--	--	--	--	--
T	T1	0	--	--	--	--	--
	T2	109	Soudan Iron Formation (SM)[2]	3	14.0	100.0%	109
U	U1	0	--	--	--	--	--
	U2	0	--	--	--	--	--
	U3	0	--	--	--	--	--
V	V1	0	--	--	--	--	--
	V2	0	--	--	--	--	--
	V3	0	--	--	--	--	--
	V4	0	--	--	--	--	--
	V5	278	Dacite (SM)	3	12.3	77.4%	215
			Soudan Iron Formation (SM)	1	3.6	22.6%	63
	V6	50	Soudan Iron Formation (SM)	1	11.9	100.0%	50
	V7	35	Unknown	--	--	--	35
	V8	648	Chert	1	4.8	16.8%	109
			Soudan Iron Formation (SM)	7	23.5	83.2%	539
Totals		171120	All	901			
		1179	Altered Unit	2			
		109	Chert	1			
		103068	Dacite (SM)	374			
		6658	Dacite/Soudan Iron Formation (SM)	13			
		1481	Gray Basalt (LE)	10			
		5526	Mafic Volcanics (SM)	63			
		2467	Metadiabase	24			
		694	Metadiabase/Dacite	4			
		162	Overburden	1			
		48196	Soudan Iron Formation (SM)	408			
		1133	Soudan Iron Formation/Altered Unit	1			
		447	Unknown	0			

Notes:
[1] No samples collected at M4, but material assumed to be dacite based on dacite-only samples from M1, M2, and M3
[2] Samples collected at T1 but not T2; Soudan Iron Formation encountered at T1 assumed also present at T2

APPENDIX E
TYPICAL GEOMEMBRANE SPECIFICATION

DROP-IN SPECIFICATIONS
STANDARD GEOMEMBRANES (METRIC UNITS)

The following drop-in specifications is a sample guideline to be customized by the engineer for preparing site specific specification. This information is provided for reference purposes only and is not intended as a warranty or guarantee. GSE assumes no liability in connection with the use of this information. Please contact GSE for current specifications.

1 GENERAL

1.1 SCOPE

This drop-in specification covers the technical requirements for the Manufacturing and Installation of the geomembrane. All materials meet or exceed the requirements of this specification, and all work will be performed in accordance with the procedures provided in these project specifications

1.2 REFERENCES

A. American Society for Testing and Materials (ASTM)
   1. D 1004 Test Method for Initial Tear Resistance of Plastic Film and Sheeting
   2. D 1238 Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer
   3. D 1505 Test Method for Density of Plastics by the Density-Gradient Technique
   4. D 1603 Test Method for Carbon Black in Olefin Plastics
   5. D 3895 Standard Test Method for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry
   6. D 4218 Standard Test Method for Determination of Carbon Black in Polyethylene Compounds
   7. D 4833 Standard Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products
   8. D 5199 Standard Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes
   9. D 5397 Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test
   10. D 5596 Standard Test Method for Microscopic Evaluation of the Dispersion of Carbon Black in Polyolefin Geosynthetics
   11. D 5994 Standard Test Method for Measuring Core Thickness of Textured Geomembranes
   12. D 6392 Standard Test Method for Determining the Integrity of Nonreinforced Geomembrane Seams Produced Using Thermo-Fusion Methods
   13. D 6693 Standard Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes
   14. D 7240 Standard Practice for Leak Location using Geomembranes with an Insulating Layer in Intimate Contact with a Conductive Layer via Electrical Capacitance Technique (Conductive Geomembrane Spark Test)

B. Geosynthetic Research Institute
   1. GRI GM 13 Test Properties, Testing Frequency and Recommended Warranty for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes
   2. GRI GM 17 Test Properties, Testing Frequency and Recommended Warranty for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes

1.3 DEFINITIONS

A. Lot - A quantity of resin (usually the capacity of one rail car) used in the manufacture of geomembranes. Finished roll will be identified by a roll number traceable to the resin lot used.

B. Construction Quality Assurance Consultant (CONSULTANT) - Party, independent from MANUFACTURER and INSTALLER that is responsible for observing and documenting activities related to quality assurance during the lining system construction.

C. ENGINEER- The individual or firm responsible for the design and preparation of the project's Contract Drawings and Specifications.
D. Geomembrane Manufacturer (MANUFACTURER) - The party responsible for manufacturing the geomembrane rolls.
E. Geosynthetic Quality Assurance Laboratory (TESTING LABORATORY) - Party, independent from the OWNER, MANUFACTURER and INSTALLER, responsible for conducting laboratory tests on samples of geosynthetics obtained at the site or during manufacturing, usually under the direction of the OWNER.
F. INSTALLER- Party responsible for field handling, transporting, storing, deploying, seaming and testing of the geomembrane seams.
G. Panel- Unit area of a geomembrane that will be seamed in the field that is larger than 9.3 m^2.
H. Patch - Unit area of a geomembrane that will be seamed in the field that is less than 9.3 m^2.
I. Subgrade Surface - Soil layer surface which immediately underlies the geosynthetic material(s).

1.4 SUBMITTALS POST-AWARD

A. Furnish the following product data, in writing, to ENGINEER prior to installation of the geomembrane material:
   1. Resin Data shall include the following.
      a. Certification stating that the resin meets the specification requirements (see Table 1.9B).
   2. Geomembrane Roll
      a. Statement certifying no recycled polymer and no more than 10% rework of the same type of material is added to the resin (product run may be recycled).

B. The INSTALLER shall furnish the following information to the ENGINEER and OWNER prior to installation:
   1. Installation layout drawings
      a. Must show proposed panel layout including field seams and details
      b. Must be approved prior to installing the geomembrane
   2. Approved drawings will be for concept only and actual panel placement will be determined by site conditions.
   3. Installer's Geosynthetic Field Installation Quality Assurance Plan

C. The INSTALLER will submit the following to the ENGINEER upon completion of installation:
   1. Certificate stating the geomembrane has been installed in accordance with the Contract Documents
   2. Material and installation warranties
   3. As-built drawings showing actual geomembrane placement and seams including typical anchor trench detail

1.5 QUALITY ASSURANCE

A. The OWNER will engage and pay for the services of a Geosynthetic Quality Assurance Consultant and Laboratory to monitor geomembrane installation.

1.6 QUALIFICATIONS

A. MANUFACTURER
   1. Geomembrane shall be manufactured by the following:
      a. GSE Lining Technology, LLC
      b. approved equal

2. MANUFACTURER shall have manufactured a minimum of 930,000 square meters of polyethylene geomembrane during the last year.

B. INSTALLER

1. Installation shall be performed by one of the following installation companies (or approved equal)
   a. GSE Lining Technology, LLC
   b. GSE Approved Installers
2. INSTALLER shall have installed a minimum of [ ] square feet of HDPE geomembrane during the [ ] last years.
3. INSTALLER shall have worked in a similar capacity on at least [ ] projects similar in complexity to the project described in the contract documents, and with at least [ ] square feet of HDPE geomembrane installation on each project.
4. The Installation Supervisor shall have worked in a similar capacity on projects similar in size and complexity to the project described in the Contract Documents.
5. The INSTALLER shall provide a minimum of one Master Seamer for work on the project.
   a. Must have completed a minimum of 93,000 square meters of geomembrane seaming work using the type of seaming apparatus proposed for the use on this Project.

1.7 MATERIAL LABELING, DELIVERY, STORAGE AND HANDLING

A. Labeling - Each roll of geomembrane delivered to the site shall be labeled by the MANUFACTURER. The label will identify:
   a. manufacturer's name
   b. product identification
   c. thickness
   d. length
   e. width
   f. roll number

B. Delivery- Rolls of liner will be prepared to ship by appropriate means to prevent damage to the material and to facilitate off-loading.

C. Storage- The on-site storage location for geomembrane material, provided by the CONTRACTOR to protect the geomembrane from punctures, abrasions and excessive dirt and moisture for should have the following characteristics:
   a. level (no wooden pallets)
   b. smooth
   c. dry
   d. protected from theft and vandalism
   e. adjacent to the area being lined

D. Handling- Materials are to be handled so as to prevent damage.

1.8 WARRANTY

A. Material shall be warranted, on a pro-rata basis against Manufacturer's defects for a period of 5 years from the date of geomembrane installation.

B. Installation shall be warranted against defects in workmanship for a period of 1 year from the date of geomembrane completion.

1.9 GEOMEMBRANE PROPERTIES

A. Material shall be smooth/textured polyethylene geomembrane as shown on the drawings.

B. Resin

1. Resin shall be new, first quality, compounded and manufactured specifically for producing geomembrane.
2. Natural resin (without carbon black) shall meet the following requirements:

Table 1.9B: Raw Material Properties

Property	Test Method	HDPE	LLDPE
Density (g/cm3)	ASTM D 1505	$\geq$0.932	$\geq$0.915
Melt Flow Index (g/10 min)	ASTM D 1238 (190/2.16)	$\leq$1.0	$\leq$1.0
OIT (minutes)	ASTM D 3895 (1 atm/200^{0}C)	$\geq$100	$\geq$100

C. Geomembrane Rolls
1. Do not exceed a combined maximum total of 1 percent by weight of additives other than carbon black.
2. Geomembrane shall be free of holes, pinholes as verified by on-line electrical detection, bubbles, blisters, excessive contamination by foreign matter, and nicks and cuts on roll edges.
3. Geomembrane material is to be supplied in roll form. Each roll is to be identified with labels indicating roll number, thickness, length, width and MANUFACTURER.
4. All liner sheets produced at the factory shall be inspected prior to shipment for compliance with the physical property requirements listed in section 1.09 D and be tested by an acceptable method of inspecting for pinholes. If pinholes are located, identified and indicated during manufacturing, these pinholes may be corrected during installation.

D. Smooth surfaced geomembrane shall meet the requirements shown in the following data sheets below:
1. Table 1.1 for Black HDPE
2. Table 1.2 for Green HDPE
3. Table 1.3 for White HDPE
   a) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   b) The white surface shall be installed upwards.
4. Table 1.4 for Smooth Leak Location Liner HDPE
   a) The geomembrane shall have a coextruded, electrically conductive layer.
   b) The conductive layer is installed downward.
   c) Electrical testing shall be performed after liner installation by the INSTALLER.
5. Table 1.6 for Smooth White Leak Location Liner HDPE
   a) The geomembrane shall have a coextruded, electrically conductive layer.
   b) The conductive layer is installed downward.
   c) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   d) The white surface shall be installed upwards.

   e) Electrical testing shall be performed after liner installation by the INSTALLER.
6. Table 1.5 for Black LLDPE
7. Table 1.6 for White-surfaced LLDPE
   a) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   b) The white surface shall be installed upwards.
8. Table 1.8 for Leak Location Liner LLDPE
   a) The geomembrane shall have a coextruded, electrically conductive layer.
   b) The conductive layer is installed downward.
   c) Electrical testing shall be performed after liner installation by the INSTALLER.

9. Table 1.9 for White Leak Location Liner LLDPE
   a) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   b) The white surface shall be installed upwards.
   c) The geomembrane shall have a coextruded, electrically conductive layer.
   d) The conductive layer is installed downward.
   e) Electrical testing shall be performed after liner installation by the INSTALLER.

Table 1.1: GSE HD Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value				
			0.75 mm	1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5199	every roll	0.750 0.675	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 20 11 700 12	 27 15 700 12	 40 22 700 12	 53 29 700 12	 67 37 700 12
Tear Resistance, N	ASTM D 1004	20,000 kg	93	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	240	320	480	640	800
Carbon Black Content, % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(1)	Note(1)	Note(1)	Note(1)	Note(1)
Notch Constant Tensile Load, hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	90,000 kg	>100	>100	>100	>100	>100
TYPICAL ROLL DIMENSIONS							
Roll Length(2), m			341	265	171	131	104
Roll Width(2), m			6.86	6.86	6.86	6.86	6.86
Roll Area, m^2			2,341	1,819	1,171	899	711

NOTES:
- (1)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (2)Roll lengths and widths have a tolerance of ±1%.
- GSE HD Smooth is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 1.2: GSE Green Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value				
			0.75 mm	1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5199	every roll	0.750 0.675	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 20 11 700 12	 27 15 700 12	 40 22 700 12	 53 29 700 12	 67 37 700 12
Tear Resistance, N	ASTM D 1004	20,000 kg	93	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	240	320	480	640	800
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(2)	Note(2)	Note(2)	Note(2)	Note(2)
Notch Constant Tensile Load, hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	90,000 kg	>100	>100	>100	>100	>100
TYPICAL ROLL DIMENSIONS							
Roll Length(3), m			341	265	171	131	104
Roll Width(3), m			6.86	6.86	6.86	6.86	6.86
Roll Area, m^2			2,341	1,819	1,171	899	711

NOTES:
- (1)GSE Green Smooth may have an overall ash content of 3.0% due to the green layer. These values apply to the black layer only.
- (2)Dispersion applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ±1%.
- GSE Green Smooth is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 1.3: GSE White Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value				
			0.75 mm	1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5199	every roll	0.750 0.675	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 20 11 700 12	 27 15 700 12	 40 22 700 12	 53 29 700 12	 67 37 700 12
Tear Resistance, N	ASTM D 1004	20,000 kg	93	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	240	320	480	640	800
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(2)	Note(2)	Note(2)	Note(2)	Note(2)
Notch Constant Tensile Load, hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	90,000 kg	>100	>100	>100	>100	>100
TYPICAL ROLL DIMENSIONS							
Roll Length(3), m			341	265	171	131	104
Roll Width(3), m			6.86	6.86	6.86	6.86	6.86
Roll Area, m^2			2,341	1,819	1,171	899	711

NOTES:
- (1)GSE White Smooth may have an overall ash content of 3.0% due to the white layer. These values apply to the black layer only.
- (2)Dispersion applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ±1%.
- GSE White Smooth is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 1.4: GSE Leak Location Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5199	every roll	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 27 15 700 12	 40 22 700 12	 53 29 700 12	 67 37 700 12
Tear Resistance, N	ASTM D 1004	20,000 kg	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	320	480	640	800
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(2)	Note(2)	Note(2)	Note(2)
Notch Constant Tensile Load, hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O2, 1 atm	90,000 kg	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(3), m			265	171	131	104
Roll Width(3), m			6.86	6.86	6.86	6.86
Roll Area, m^2			1,819	1,171	899	711

NOTES:
- (1)GSE Leak Location Smooth may have an overall ash content of 3.0% due to the conductive layer. These values apply to the black layer only.
- (2)Dispersion applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ± 1%.
- GSE Leak Location Smooth is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 1.5: GSE Leak Location White Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5199	every roll	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 27 15 700 12	 40 22 700 12	 53 29 700 12	 67 37 700 12
Tear Resistance, N	ASTM D 1004	20,000 kg	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	320	480	640	800
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(2)	Note(2)	Note(2)	Note(2)
Notch Constant Tensile Load, hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	90,000 kg	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(3), m			265	171	131	104
Roll Width(3), m			6.86	6.86	6.86	6.86
Roll Area, m^2			1,819	1,171	899	711

NOTES:
- (1)GSE Leak Location White Smooth may have an overall ash content of 3.0% due to the white and conductive layers. These values apply to the black layer only.
- (2)Dispersion applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ± 1%.
- GSE Leak Location White Smooth is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 1.6: GSE UltraFlex Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm^3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 152 800	 228 800	 304 800	 380 800
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	56	84	112	140
Carbon Black Content, % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note(1)	Note(1)	Note(1)	Note(1)
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(2), ft			870	560	430	340
Roll Width(2), ft			22.5	22.5	22.5	22.5
Roll Area, ft^2			19,575	12,600	9,675	7,650

NOTES:
- (1)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (2)Roll lengths and widths have a tolerance of ±1 %.
- GSE UltraFlex is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

Table 1.7: GSE UltraFlex White Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 152 800	 228 800	 304 800	 380 800
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	56	84	112	140
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note(2)	Note(2)	Note(2)	Note(2)
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(3), ft			870	560	430	340
Roll Width(3), ft			22.5	22.5	22.5	22.5
Roll Area, ft^2			19,575	12,600	9,675	7,650

NOTES:
- (1)GSE UltraFlex White Smooth may have an overall ash content greater than 3.0% due to the white layer. These values apply to the black layer only.
- (2)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ±1%.
- GSE UltraFlex White Smooth is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

Table 1.8: GSE UltraFlex Leak Location Liner Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm^3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 152 800	 228 800	 304 800	 380 800
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	56	84	112	140
Carbon Black Content[(1)], % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note[(2)]	Note[(2)]	Note[(2)]	Note[(2)]
Oxidative Induction Time, min	ASTM D 3895, 200°C; O2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length[(3)], ft			870	560	430	340
Roll Width[(3)], ft			22.5	22.5	22.5	22.5
Roll Area, ft^2			19,575	12,600	9,675	7,650

NOTES:
- [(1)]GSE UltraFlex Leak Location Smooth may have an overall ash content greater than 3.0% due to the conductive layer. These values apply to the non-conductive black layer only.
- [(2)]Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- [(3)]Roll lengths and widths have a tolerance of ±1%.
- GSE UltraFlex Leak Location Smooth is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

Table 1.9: GSE UltraFlex White Leak Location Liner White Smooth Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm^3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 152 800	 228 800	 304 800	 380 800
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	56	84	112	140
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note(2)	Note(2)	Note(2)	Note(2)
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(3), ft			870	560	430	340
Roll Width(3), ft			22.5	22.5	22.5	22.5
Roll Area, ft^2			19,575	12,600	9,675	7,650

NOTES:
- (1)GSE UltraFlex Leak Location White Smooth may have an overall ash content greater than 3.0% due to the white and conductive layers. These values apply to the non-conductive black layer only.
- (2)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ±1%.
- GSE UltraFlex Leak Location White Smooth is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

E. Textured surfaced geomembrane shall meet the requirements shown in the following data sheets below.

1. Table 2.1 for Black coextruded textured HDPE
2. Table 2.2 for Green coextruded textured HDPE
3. Table 2.3 for White coextruded textured HDPE
   a) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   b) The white surface shall be installed upwards.
4. Table 2.4 for Leak Location Liner textured HDPE
   a) The geomembrane shall have a coextruded, electrically conductive layer.
   b) The conductive layer is installed downward.
   c) Electrical testing shall be performed after liner installation by the INSTALLER.
5. Table 2.5 for White Leak Location Liner textured HDPE
   a) The geomembrane shall have a coextruded, electrically conductive layer.
   b) The conductive layer is installed downward.
   c) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   d) The white surface shall be installed upwards.
6. Table 2.6 for Black coextruded textured LLDPE
7. Table 2.7 for White coextruded textured LLDPE
   a) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   b) The white surface shall be installed upwards.
8. Table 2.8 for Leak Location coextruded textured LLDPE
   a) The geomembrane shall have a coextruded, electrically conductive layer.
   b) The conductive layer is installed downward.
   e) Electrical testing shall be performed after liner installation by the INSTALLER.
9. Table 2.9 for White Leak Location coextruded textured LLDPE
   a) The geomembrane shall have a coextruded, electrically conductive layer.
   b) The conductive layer is installed downward.
   c) The geomembrane shall be a white-surfaced, coextruded geomembrane.
   d) The white surface shall be installed upwards.
   e) Electrical testing shall be performed after liner installation by the INSTALLER.

Table 2.1: GSE HD Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value				
			0.75 mm	1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5994	every roll	0.750 0.675	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3 , (min.)	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 8 11 100 12	 10 15 100 12	 16 22 100 12	 21 29 100 12	 26 37 100 12
Tear Resistance, N	ASTM D 1004	20,000 kg	93	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	200	267	400	534	667
Carbon Black Content, % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(1)	Note(1)	Note(1)	Note(1)	Note(1)
Asperity Height, mm	ASTM D 7466	second roll	0.40	0.45	0.45	0.45	0.45
Notch Constant Tensile Load(2), hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	90,000 kg	>100	>100	>100	>100	>100
TYPICAL ROLL DIMENSIONS							
Roll Length(3), m	Double-Sided Textured Single-Sided Textured		253 308	213 238	158 165	122 125	101 101
Roll Width(3), m			6.86	6.86	6.86	6.86	6.86
Roll Area, m^2	Double-Sided Textured Single-Sided Textured		1,736 2,113	1,461 1,633	1,084 1,132	837 858	693 693

NOTES:
- (1)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (2)NCTL for GSE HD Textured is conducted on representative smooth geomembrane samples.
- (3)Roll lengths and widths have a tolerance of ±1%.
- GSE HD Textured is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 2.2: GSE Green Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value				
			0.75 mm	1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5994	every roll	0.750 0.675	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3 , (min.)	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 8 11 100 12	 10 15 100 12	 16 22 100 12	 21 29 100 12	 26 37 100 12
Tear Resistance, N	ASTM D 1004	20,000 kg	93	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	200	267	400	534	667
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(2)	Note(2)	Note(2)	Note(2)	Note(2)
Asperity Height, mm	ASTM D 7466	second roll	0.40	0.45	0.45	0.45	0.45
Notch Constant Tensile Load(3), hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O2, 1 atm	90,000 kg	>100	>100	>100	>100	>100
TYPICAL ROLL DIMENSIONS							
Roll Length(4), m	Double-Sided Textured Single-Sided Textured		253 308	213 238	158 165	122 125	101 101
Roll Width(4), m			6.86	6.86	6.86	6.86	6.86
Roll Area, m^2	Double-Sided Textured Single-Sided Textured		1,736 2,113	1,461 1,633	1,084 1,132	837 858	693 693

NOTES:
- (1)GSE Green may have an overall ash content greater than 3.0% due to the green layer. These values apply to the black layer only.
- (2)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)NCTL for GSE Green Textured is conducted on representative smooth geomembrane samples.
- (4)Roll lengths and widths have a tolerance of ±1%.
- GSE Green Textured is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 2.3: GSE White Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Value				
			0.75 mm	1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5994	every roll	0.750 0.675	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3 , (min.)	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 51 mm G.L. 33 mm	9,000 kg	 8 11 100 12	 10 15 100 12	 16 22 100 12	 21 29 100 12	 26 37 100 12
Tear Resistance, N	ASTM D 1004	20,000 kg	93	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	200	267	400	534	667
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(2)	Note(2)	Note(2)	Note(2)	Note(2)
Asperity Height, mm	ASTM D 7466	second roll	0.40	0.45	0.45	0.45	0.45
Notch Constant Tensile Load(3), hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	90,000 kg	>100	>100	>100	>100	>100
TYPICAL ROLL DIMENSIONS							
Roll Length(4), m	Double-Sided Textured Single-Sided Textured		253 308	213 238	158 165	122 125	101 101
Roll Width(4), m			6.86	6.86	6.86	6.86	6.86
Roll Area, m^2	Double-Sided Textured Single-Sided Textured		1,736 2,113	1,461 1,633	1,084 1,132	837 858	693 693

NOTES:

- (1)GSE White may have an overall ash content greater than 3.0% due to the white layer. These values apply to the black layer only.
- (2)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)NCTL for GSE White Textured is conducted on representative smooth geomembrane samples.
- (4)Roll lengths and widths have a tolerance of ±1%.
- GSE White Textured is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 2.4: GSE Leak Location Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5994	every roll	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 10 15 100 12	 16 22 100 12	 21 29 100 12	 26 37 100 12
Tear Resistance, N	ASTM D 1004	20,000 kg	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	267	400	534	667
Carbon Black Content[(1)], % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note[(2)]	Note[(2)]	Note[(2)]	Note[(2)]
Asperity Height, mm	ASTM D 7466	second roll	0.45	0.45	0.45	0.45
Notch Constant Tensile Load[(3)], hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	90,000 kg	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length[(4)], m	Double-Sided Textured Single-Sided Textured		213 238	158 165	122 125	101 101
Roll Width[(4)], m			6.86	6.86	6.86	6.86
Roll Area, m^2	Double-Sided Textured Single-Sided Textured		1,461 1,633	1,084 1,132	837 858	693 693

NOTES:
- [(1)]GSE Leak Location may have an overall ash content greater than 3.0% due to the conductive layer. These values apply to the non-conductive layer only.
- [(2)]Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- [(3)]NCTL for GSE Leak Location Textured is conducted on representative smooth geomembrane samples.
- [(4)]Roll lengths and widths have a tolerance of ±1%.
- GSE Leak Location Textured is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 2.5: GSE Leak Location White Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			1.00 mm	1.50 mm	2.00 mm	2.50 mm
Thickness, (minimum average), mm Lowest individual reading	ASTM D 5994	every roll	1.00 0.90	1.50 1.35	2.00 1.80	2.50 2.25
Density, g/cm^3	ASTM D 1505	90,000 kg	0.940	0.940	0.940	0.940
Tensile Properties (each direction) Strength at Break, N/mm Strength at Yield, N/mm Elongation at Break, % Elongation at Yield, %	ASTM D 6693, Type IV Dumbbell, 50 mm/min G.L. 50 mm G.L. 33 mm	9,000 kg	 10 15 100 12	 16 22 100 12	 21 29 100 12	 26 37 100 12
Tear Resistance, N	ASTM D 1004	20,000 kg	125	187	249	311
Puncture Resistance, N	ASTM D 4833	20,000 kg	267	400	534	667
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	9,000 kg	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	20,000 kg	Note(2)	Note(2)	Note(2)	Note(2)
Asperity Height, mm	ASTM D 7466	second roll	0.45	0.45	0.45	0.45
Notch Constant Tensile Load(3), hr	ASTM D 5397, Appendix	90,000 kg	300	300	300	300
Oxidative Induction Time, min	ASTM D 3895, 200°C; O2, 1 atm	90,000 kg	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(4), m	Double-Sided Textured Single-Sided Textured		213 238	158 165	122 125	101 101
Roll Width(4), m			6.86	6.86	6.86	6.86
Roll Area, m^2	Double-Sided Textured Single-Sided Textured		1,461 1,633	1,084 1,132	837 858	693 693

NOTES:
- (1)GSE Leak Location White may have an overall ash content greater than 3.0% due to the conductive and white layers. These values apply to the non-conductive black layer only.
- (2)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)NCTL for GSE Leak Location White Textured is conducted on representative smooth geomembrane samples.
- (4)Roll lengths and widths have a tolerance of ±1%.
- GSE Leak Location White Textured is available in rolls weighing approximately 1,800 kg.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77° C when tested according to ASTM D 746.
- *Modified.

Table 2.6: GSE UltraFlex Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm^3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 60 250	 90 250	 120 250	 150 250
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	44	66	88	110
Carbon Black Content, % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note(1)	Note(1)	Note(1)	Note(1)
Asperity Height, mil	ASTM D 7466	second roll	18	18	18	18
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(2), ft	Double-Sided Textured Single-Sided Textured		700 650	520 420	400 320	330 250
Roll Width(2), ft			22.5	22.5	22.5	22.5
Roll Area, ft^2	Double-Sided Textured Single-Sided Textured		15,750 14,625	11,700 9,450	9,000 7,200	7,425 5,625

NOTES:
- (1)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (2)Roll lengths and widths have a tolerance of ±1%.
- GSE UltraFlex Textured is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

Table 2.7: GSE UltraFlex White Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm^3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 60 250	 90 250	 120 250	 150 250
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	44	66	88	110
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note(2)	Note(2)	Note(2)	Note(2)
Asperity Height, mil	ASTM D 7466	second roll	18	18	18	18
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(3), ft	Double-Sided Textured Single-Sided Textured		700 650	520 420	400 320	330 250
Roll Width(3), ft			22.5	22.5	22.5	22.5
Roll Area, ft^2	Double-Sided Textured Single-Sided Textured		15,750 14,625	11,700 9,450	9,000 7,200	7,425 5,625

NOTES:
- (1)GSE UltraFlex White Textured may have an overall ash content greater than 3.0% due to the white layer. These values apply to the black layer only.
- (2)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ±1%.
- GSE UltraFlex White Textured is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

Table 2.8: GSE UltraFlex Leak Location Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm^3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 60 250	 90 250	 120 250	 150 250
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	44	66	88	110
Carbon Black Content(1), % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note(2)	Note(2)	Note(2)	Note(2)
Asperity Height, mil	ASTM D 7466	second roll	18	18	18	18
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length(3), ft	Double-Sided Textured Single-Sided Textured		700 650	520 420	400 320	330 250
Roll Width(3), ft			22.5	22.5	22.5	22.5
Roll Area, ft^2	Double-Sided Textured Single-Sided Textured		15,750 14,625	11,700 9,450	9,000 7,200	7,425 5,625

NOTES:
- (1)GSE UltraFlex Leak Location Textured may have an overall ash content greater than 3.0% due to the conductive layer. These values apply to the non-conductive black layer only.
- (2)Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- (3)Roll lengths and widths have a tolerance of ±1%.
- GSE UltraFlex Leak Location Textured is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

Table 2.9: GSE UltraFlex Leak Location White Textured Geomembrane (Metric)

Tested Property	Test Method	Frequency	Minimum Average Values			
			40 mil	60 mil	80 mil	100 mil
Thickness, mil Lowest individual reading	ASTM D 5199	every roll	40 36	60 54	80 72	100 90
Density, g/cm^3 (max.)	ASTM D 1505	200,000 lbs	0.939	0.939	0.939	0.939
Tensile Properties (each direction) Strength at Break, lb/in-width Elongation at Break, %	ASTM D 6693, Type IV Dumbbell, 2 ipm G.L. 2.0 in	20,000 lbs	 60 250	 90 250	 120 250	 150 250
Tear Resistance, lb	ASTM D 1004	45,000 lbs	22	33	44	55
Puncture Resistance, lb	ASTM D 4833	45,000 lbs	44	66	88	110
Carbon Black Content[(1)], % (Range)	ASTM D 1603*/4218	20,000 lbs	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
Carbon Black Dispersion	ASTM D 5596	45,000 lbs	Note[(2)]	Note[(2)]	Note[(2)]	Note[(2)]
Asperity Height, mil	ASTM D 7466	second roll	18	18	18	18
Oxidative Induction Time, min	ASTM D 3895, 200°C; O_2, 1 atm	200,000 lbs	>100	>100	>100	>100
Typical Roll Dimensions						
Roll Length[(3)], ft	Double-Sided Textured Single-Sided Textured		700 650	520 420	400 320	330 250
Roll Width[(3)], ft			22.5	22.5	22.5	22.5
Roll Area, ft^2	Double-Sided Textured Single-Sided Textured		15,750 14,625	11,700 9,450	9,000 7,200	7,425 5,625

NOTES:
- [(1)]GSE UltraFlex Leak Location White Textured may have an overall ash content greater than 3.0% due to the white and conductive layers. These values apply to the non-conductive black layer only.
- [(2)]Dispersion only applies to near spherical agglomerates. 9 of 10 views shall be Category 1 or 2. No more than 1 view from Category 3.
- [(3)]Roll lengths and widths have a tolerance of ±1%.
- GSE UltraFlex Leak Location White Textured is available in rolls weighing approximately 4,000 lb.
- All GSE geomembranes have dimensional stability of ±2% when tested according to ASTM D 1204 and LTB of <-77°C when tested according to ASTM D 746.
- *Modified.

F. Extrudate Rod or Bead
1. Extrudate material shall be made from same type resin as the geomembrane.
2. Additives shall be thoroughly dispersed.
3. Materials shall be free of contamination by moisture or foreign matter.

1.10 EQUIPMENT

A. Welding equipment and accessories shall meet the following requirements:
1. Gauges showing temperatures in apparatus such as extrusion welder or fusion welder shall be present.
2. An adequate number of welding apparati shall be available to avoid delaying work.
3. Power source must be capable of providing constant voltage under combined line load.

1.11 DEPLOYMENT

A. Assign each panel a simple and logical identifying code. The coding system shall be subject to approval and shall be determined at the job site.
B. Visually inspect the geomembrane during deployment for imperfections and mark faulty or suspect areas.
C. Deployment of geomembrane panels shall be performed in a manner that will comply with the following guidelines:
1. Geomembranes shall be installed according to site-specific specifications, and GSE Conductive should be installed with the Conductive layer down.
Note: A spark tester or ohm meter can be used to determine Conductive layer.
2. Unroll geomembrane using methods that will not damage geomembrane and will protect underlying surface from damage (spreader bar, protected equipment bucket).
3. Place ballast (commonly sandbags) on geomembrane which will not damage geomembrane to prevent wind uplift.
4. Personnel walking on geomembrane shall not engage in activities or wear shoes that could damage it. Smoking will not be permitted on the geomembrane.
5. Do not allow heavy vehicular traffic directly on geomembrane. Rubber-tired ATV's and trucks are acceptable if wheel contact is less than 55 kPa.
6. Protect geomembrane in areas of heavy traffic by placing protective cover over the geomembrane.

D. Sufficient material (slack) shall be provided to allow for thermal expansion and contraction of the material.

1.12 FIELD SEAMING

A. Seams shall meet the following requirements:
1. To the maximum extent possible, orient seams parallel to line of slope, i.e., down and not across slope.
2. Minimize number of field seams in corners, odd-shaped geometric locations and outside corners.
3. Slope seams (panels) shall extend a minimum of 1.5 meters beyond the grade break into the flat area.
4. Use a sequential seam numbering system compatible with panel numbering system that is agreeable to the CONSULTANT and INSTALLER.

5. Align seam overlaps consistent with the requirements of the welding equipment being used. A 15.2 cm overlap is commonly suggested.

B. During Welding Operations

1. Provide at least one Master Seamer who shall provide direct supervision over other welders as necessary.

C. Extrusion Welding

1. Hot-air tack adjacent pieces together using procedures that do not damage the geomembrane.
2. Clean geomembrane surfaces by disc grinder or equivalent.
3. Purge welding apparatus of heat-degraded extrudate before welding.

D. Hot Wedge Welding

1. Welding apparatus shall be a self-propelled device equipped with an electronic controller which displays applicable temperatures.
2. Clean seam area of dust, mud, moisture and debris immediately ahead of hot wedge welder.
3. Protect against moisture build-up between sheets.

E. Trial Welds

1. Perform trial welds on geomembrane samples to verify welding equipment is operating properly.
2. Make trial welds under the same surface and environmental conditions as the production welds, i.e., in contact with subgrade and similar ambient temperature.
3. Minimum of two trial welds per day, per welding apparatus, one made prior to the start of work and one completed at mid shift.
4. Cut four, 2.5 cm wide by 15.2 cm long test strips from the trial weld.
5. Quantitatively test specimens for peel adhesion, and then for shear strength.
6. Trial weld specimens shall pass when the results shown in the following tables for HDPE and LLDPE are achieved in both peel and shear test.

Table 1.12.6A: Minimum Weld Values for HDPE Geomembranes (Metric)

Property	Test Method	0.75	1.0	1.5	2.0	2.5	3.0
Peel Strength (fusion), kN/m Peel Strength (extrusion), kN/m	ASTM D 6392 ASTM D 6392	8.6 6.8	11.4 9.1	17.2 13.7	22.8 18.2	28.4 22.8	34.3 27.5
Shear Strength (fusion & ext.), kN/m	ASTM D 6392	10.7	14.2	21.2	28.4	35.5	42.4

Table 1.2.6B: Minimum Weld Values for LLDPE Geomembranes (Metric)

Property	Test Method	0.75	1.0	1.5	2.0	2.5
Peel Strength (extrusion), kN/m Peel Strength (fusion), kN/m	ASTM D 6392 ASTM D 6392	6.3 6.7	8.4 8.8	12.6 13.1	16.8 17.5	21.0 21.9
Shear Strength (fusion & ext.), kN/m	ASTM D 6392	7.9	10.5	15.8	21.0	26.3

a. The break, when peel testing, occurs in the liner material itself, not through peel separation (FTB).
b. The break is ductile.

7. Repeat the trial weld, in its entirety, when any of the trial weld samples fail in either peel or shear.
8. No welding equipment or welder shall be allowed to perform production welds until equipment and welders have successfully completed trial weld.

F. Seaming shall not proceed when ambient air temperature or adverse weather conditions jeopardize the integrity of the liner installation. INSTALLER shall demonstrate that acceptable seaming can be performed by completing acceptable trial welds.

G. Defects and Repairs
   1. Examine all seams and non-seam areas of the geomembrane for defects, holes, blisters, undispersed raw materials, and any sign of contamination by foreign matter.
   2. Repair and non-destructively test each suspect location in both seam and non-seam areas. Do not cover geomembrane at locations that have been repaired until test results with passing values are available.

1.13 FIELD QUALITY ASSURANCE

A. MANUFACTURER and INSTALLER shall participate in and conform to all terms and requirements of the Owner's quality assurance program. CONTRACTOR shall be responsible for assuring this participation.

B. Quality assurance requirements are as specified in this Section and in the Field Installation Quality Assurance Manual if it is included in the contract.

C. Field Testing
   1. Non-destructive testing may be carried out as the seaming progresses or at completion of all field seaming.
      a. Vacuum Testing
         1) Shall be performed in accordance with ASTM D 5641, Standard Practice for Geomembrane Seam Evaluation by Vacuum Chamber.
      b. Air Pressure Testing
         1) Shall be performed in accordance with ASTM D 5820, Standard Practice for Pressurized Air Channel Evaluation of Dual Seamed Geomembranes.
      c. Spark Tesing
         1) Shall be performed accordance with ASTM D 7240 Standard Practice for Leak Location using Geomembranes with an Insulating Layer in Intimate Contact with a Conductive Layer via Electrical Capacitance Technique (Conductive Geomembrane Spark Test).
      d. Other approved methods.
   2. Destructive Testing (performed by CONSULTANT with assistance from INSTALLER)
      a. Location and Frequency of Testing
         1) Collect destructive test samples at a frequency of one per every 152 meters of seam length.
         2) Test locations will be determined after seaming.
         3) Exercise Method of Attributes as described by GRI GM-14 (Geosynthetic Research Institute, http://www.geosynthetic-institute.org) to minimize test samples taken.
      b. Sampling Procedures are performed as follows:
         1) INSTALLER shall cut samples at locations designated by the CONSULTANT as the seaming progresses in order to obtain field laboratory test results before the geomembrane is covered.
         2) CONSULTANT will number each sample, and the location will be noted on the installation as-built.
         3) Samples shall be 30.5 cm wide by minimal length with the seam centered lengthwise.
         4) Cut a 5.1 cm wide strip from each end of the sample for field-testing.
         5) Cut the remaining sample into two parts for distribution as follows:
            a) One portion for INSTALLER, 30.5 cm by 30.5 cm
            b) One portion for the Third Party laboratory, 30.5 cm by 45.7 cm
            c) Additional samples may be archived if required.

6) Destructive testing shall be performed in accordance with ASTM D 6392, Standard Test Method for Determing the Integrity of Non-Reinforced Geomembrane Seams Produced Using Thermo-Fusion Methods.
7) INSTALLER shall repair all holes in the geomembrane resulting from destructive sampling.
8) Repair and test the continuity of the repair in accordance with these Specifications.

3. Failed Seam Procedures
   a) If the seam fails, INSTALLER shall follow one of two options:
      1) Reconstruct the seam between any two passed test locations.
      2) Trace the weld to intermediate location at least 3 meters minimum or where the seam ends in both directions from the location of the failed test.
   b) The next seam welded using the same welding device is required to obtain an additional sample, i.e., if one side of the seam is less than 3 meters long.
   c) If sample passes, then the seam shall be reconstructed or capped between the test sample locations.
   d) If any sample fails, the process shall be repeated to establish the zone in which the seam shall be reconstructed.

1.14 REPAIR PROCEDURES

A. Remove damaged geomembrane and replace with acceptable geomembrane materials if damage cannot be satisfactorily repaired.
B. Repair any portion of unsatisfactory geomembrane or seam area failing a destructive or non-destructive test.
C. INSTALLER shall be responsible for repair of defective areas.
D. Agreement upon the appropriate repair method shall be decided between CONSULTANT and INSTALLER by using one of the following repair methods:
   1. Patching- Used to repair large holes, tears, undispersed raw materials and contamination by foreign matter.
   2. Abrading and Re-welding- Used to repair short section of a seam.
   3. Spot Welding- Used to repair pinholes or other minor, localized flaws or where geomembrane thickness has been reduced.
   4. Capping- Used to repair long lengths of failed seams.
   5. Flap Welding- Used to extrusion weld the flap (excess outer portion) of a fusion weld in lieu of a full cap.
   6. Remove the unacceptable seam and replace with new material.
E. The following procedures shall be observed when a repair method is used:
   1. All geomembrane surfaces shall be clean and dry at the time of repair.
   2. Surfaces of the polyethylene which are to be repaired by extrusion welds shall be lightly abraded to assure cleanliness.
   3. Extend patches or caps at least 15.2 cm for extrusion welds and 10.2 cm for wedge welds beyond the edge of the defect, and around all corners of patch material.
F. Repair Verification
   1. Number and log each patch repair (performed by CONSULTANT).
   2. Non-destructively test each repair using methods specified in this Specification.

1.15 MEASUREMENT AND PAYMENT

A. Payment for geomembrane installation will be as per contract unit price per square foot, as measured parallel to liner surface, including designed anchor trench material and is based upon net lined area.

B. Net lined area is defined to be the true area of all surfaces to be lined plus designed burial in all anchor trenches, rubsheets, and sacrificial layers.

C. Prices shall include full compensation for furnishing all labor, material, tools, equipment, and incidentals.

D. Prices also include doing all the work involved in performing geomembrane installation completely as shown on the drawing, as specified herein, and as directed by the ENGINEER.

END OF SECTION

APPENDIX F
MNDOT GEOTEXTILE SPECIFICATION

3733 GEOTEXTILES

3733.1 SCOPE

Provide geotextiles (permeable fabrics) for the typical uses classified as follows:

(1) Type 1 for wrapping subsurface drain pipe, joints of concrete pipe culvert, or other drainage applications;
(2) Type 2. The Department no longer uses this classification. If the contract specifies Type II, use Type III property requirements;
(3) Type 3 for use under Class 1 and Class 2 random riprap, gabions, and revetment mattresses;
(4) Type 4 for use under Class 3 and Class 4 random riprap and hand-placed riprap on slopes no steeper than 1:3, vertical to horizontal;
(5) Type 5 for separating materials for stabilization;
(6) Type 6 for earth reinforcement;
(7) Type 7 for use under Class 3 and Class 4 random riprap on slopes steeper than 1:3, vertical to horizontal, and under Class 5 random riprap.
(8) Type 8 for use as a bond breaker interlayer for concrete overlays over existing concrete pavement.

3733.2 REQUIREMENTS

A General

Provide geotextiles consisting of woven, nonwoven, or knit fabric of polymeric filaments or yarns, such as polypropylene, polyethylene, polyester, or polyamide, that form a stable network. Knit fabric shall only be used as perforated pipe wrap. Provide geotextile resistant to biological and chemical environments normally found in soils, and that is free of chemical treatment or coating that may significantly reduce porosity or permeability.

Provide geotextile that is uniform in texture, thickness, and appearance, and is free of defects, flaws, or tears that may alter the strength or filtering properties. Repair geotextile as approved by the Engineer.

Deliver rolls of geotextile or geotextile-wrapped perforated pipe with an opaque plastic covering to protect the material from ultraviolet rays or contamination with mud, dirt, dust, or debris. Provide rolled geotextile labeled on the outside wrap and inside the core in accordance with ASTM D 4873 and as follows:

(1) Manufacturer,
(2) Product name, and
(3) Roll number.

Ensure unprotected geotextile is not exposed to sun for more than seven days. Replace contaminated geotextile or geotextile exposed to the sun for more than seven days, if directed by the Engineer.

Provide geotextile meeting the requirements of Table 3733-1 or Table 3733-2 for the type required by the contract.

If using Type 5 or Type 6 geotextile, produce seams meeting the requirements of Table 3733-1, row B3, "Seam Breaking Strength Minimum."

B Physical Properties

Table 3733-1
Geotextile Properties

Geotextile Property	Test Method (ASTM) / Units	Type (a) 1 Fabric	1 Knit sock (b)	3	4	5	6	7 (c)	8(h)
B1 Grab Tensile Strength minimum, each principal direction	D4632 lb	100	—	100	200	200	(d)	300	—
B2 Elongation minimum, each principal direction	D4632 percent	—	—	50	50	—	(d)	50	—
B3 Seam Breaking Strength minimum (e)	D4632 lb	90	—	90	180	180	(d)	270	—
B4 Apparent Opening Size (AOS) maximum (f)	D4751 U.S. Std. sieve size [mm]	40	40 as applied	50	50	30	20	50	—
B5 Permittivity minimum (g)	D4491 falling head sec^{-1}	0.7	2.75 relaxed	0.5	0.5	0.05	0.05	0.5	—

Table 3733-1
Geotextile Properties

B6 Puncture strength minimum	D6241 lb	—	180	—	—	—	—	—	—
B7 Wide Width Strip Tensile Strength minimum each principal direction	D4595 lb/ft	—	—	—	—	—	(d)	—	—

(a) Minimum Average Roll Values (MARV) based on average of at least three tests per swatch.
(b) Provide socks made of knit polymeric materials and meeting the requirements of ASTM D6707-06, for Type H: fabric. Ensure the sock exhibits minimum snag or run potential, is factory-applied to maintain uniform installed mass, and conforms to the outside diameter of the tubing with a snug fit.
(c) Needle-punched nonwoven. Do not use thermally bonded (heat-set) fabric.
(d) Requirements are site-specific and will be as specified in the contract. The property values for B1 and B3 may not be less than shown for Type 5. If the contract does not specify either B1 or B7, use a default value of 300 lb for B1. If the contract does not specify seam strength, use a default value of 270 lb for B3.
(e) Adhere to this requirement if the contract requires or allows seams. Strength specifications apply to factory and field seams. Use thread for sewing that has strength of at least 25 lb. Sew seams with a Federal Type 401 stitch using a two-spool sewing machine, and install seams facing upward. For seaming with adhesives, see the Approved/Qualified Products List available at the Department's website.
(f) For U.S. sieve sizes, the AOS Number must be equal to or greater than the number specified.
(g) Permittivity: P = K/L, where K = fabric permeability and L = fabric thickness.
(h) See Table 3733.2 for requirements.

Table 3733-2
Non-woven Geotextile Interlayer Material for Concrete Overlay

Property	Requirements[1]	Test Procedure
Geotextile type	Nonwoven, needle-punched geotextile, no thermal treatment (calendaring or IR)	Manufacturer Certificate of Compliance
Color	Uniform/nominally same-color fibers	Visual Inspection
Mass per unit area	≥ 14.7 oz/yd^2	ASTM D 5261
Thickness under load (pressure)	[a] At 0.29 psi [2 kPa]: ≥ 0.12 in [b] At 2.9 psi [20 kPa]: ≥ 0.10 in [c] At 29 psi [200 kPa]: ≥ 0.04 in	ASTM D 5199
Wide-width tensile strength	≥ 685 lb/ft	ASTM D 4595
Wide-width maximum elongation	≤ 130%	ASTM D 4595
Water permeability in normal direction under load (pressure)	At 2.9 psi: ≥ 3.3x10-4 ft/s	Mod. ASTM D 5493 or ASTM D 4491
In-plane water permeability (transmissivity) under load (pressure)	[a] At 2.9 psi: ≥ 1.6x10-3 ft/s [b] At 29 psi: ≥ 6.6x10-4 ft/s	Mod. ASTM D 6574 or ASTM D 4716
Weather resistance	Retained strength ≥ 60%	ASTM D 4355 @ 500 hrs. exposure
Alkali resistance	≥ 96% polypropylene/polyethylene	Manufacturer certification of polymer

3733.3 SAMPLING AND TESTING

A Certificate of Compliance

Ensure the supplier submits to the Engineer a Certificate of Compliance and a document stating the manufacturer's MARV with each shipment of geotextile. MARV are two standard deviations below the mean value of all rolls tested. Provide a copy of the Certificate of Compliance and MARV with each geotextile sample sent to the Materials Laboratory for testing.

B Sampling and Testing

The Department's inspection and test results will determine acceptance of the geotextile, in accordance with 1603.4, "Acceptance." In the presence of the Engineer, randomly select samples in the field at the rates and sample sizes shown in the Schedule of Materials Control. Cut samples across the full width of the roll. Do not sample the first full turn (outside layer) of the roll. Provide seam samples in addition to the regular sample. Use the same machine, or an equal machine to the one on the project, to produce seam samples.