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MnDOT Highway 169
2015 Drilling Project

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INTRODUCTION

The Natural Resources Research Institute (NRRI) Economic Geology Group was contracted by the Minnesota Department of Transportation (MnDOT) [Project Number 0005269] to provide onsite drilling supervision, core logging and sampling, and geochemical studies related to proposed construction along Highway 169 east of Soudan, Minnesota. The goal of this project was to provide MnDOT the data required to produce a mitigation plan for the Highway 169 Eagles Nest project. MnDOT, working with the Minnesota Department of Natural Resources (DNR) and Golder Associates, was responsible for developing the guidelines for this work with the help of the Highway 169 Technical Working Group (Minnesota Pollution Control Agency, Minnesota Department of Health, US Corps of Engineers, Environmental Protection Agency, and NRRI). Golder Associates (Seattle, WA office) was responsible for developing the mitigation plan for bedrock roadcuts along the reroute. This work was a continuation of the studies by Severson and Heine (2010, 2012) and Heine (2015) which examined the bedrock outcrops along three proposed Highway 169 reroutes and alternatives. Severson and Heine (2012) concluded that drilling would be needed in the potential bedrock roadcuts along the reroute corridor to fully characterize the geology as required in the mitigation plan.

One hundred and eighty-two drill holes, ranging in depth from 9 feet to 83.5 feet, were drilled by Idea Drilling, Virginia, Minnesota, between August and December of 2015 along the proposed highway construction corridor bedrock roadcuts (Figure 1). A total of 777 drill core samples were collected from the drill holes for Acid-Base Accounting (ABA) and, where necessary, for trace metals analysis (performed by ALS Minerals, Thunder Bay, Ont).

All data collected by the NRRI (Appendices A-K) has previously been given to MnDOT during the field component of the project. MnDOT was responsible for distributing the data to Golder Associates, Minnesota DNR, and the Highway 169 Technical Working Group. Data provided previously and contained in this report includes:

1. Appendix A - Field data including modifications to planned drill hole locations, quick logs, water level testing and surveyed locations for the drill holes UTMs (NAD83) (provided by MnDOT employees). Three previous reports (Severson and Heine (2010, 2012) and Heine (2015)) contain field data from outcrop mapping;
2. Appendix B - Field drill logs used to quickly inform MnDOT what was drilled as requested;
3. Appendix C - MnDOT drill hole logs and rock quality data (RQD), filled out by both the field and logging teams for integration into MnDOT's drill log database;
4. Appendix D - Field photos taken to document the drill site, drilling and abandonment of the drill holes, and the drill core on site;
5. Appendix E - NRRI drill hole logs including lithology, alteration and weathering, and sulfide mineral estimates;
6. Appendix F - Summary drill hole log spreadsheet;
7. Appendix G - Drill core photos taken after logging and determination of sample intervals;
8. Appendix H - Cross-Sections of the drill holes by roadcut and drill line;
9. Appendix I - Downhole graphical drill logs and Leco sulfur analyses;
10. Appendix J - ALS Minerals geochemistry, including Certificates of Analysis, Quality control Certificate, and Invoices for each batch run ALS Minerals for the project;
11. Appendix K - Summary geochemistry spreadsheet, combining all of the ALS Minerals geochemistry data; and
12. Appendix L: Plate 1 – Geologic Map of the Eagles Nest Project.

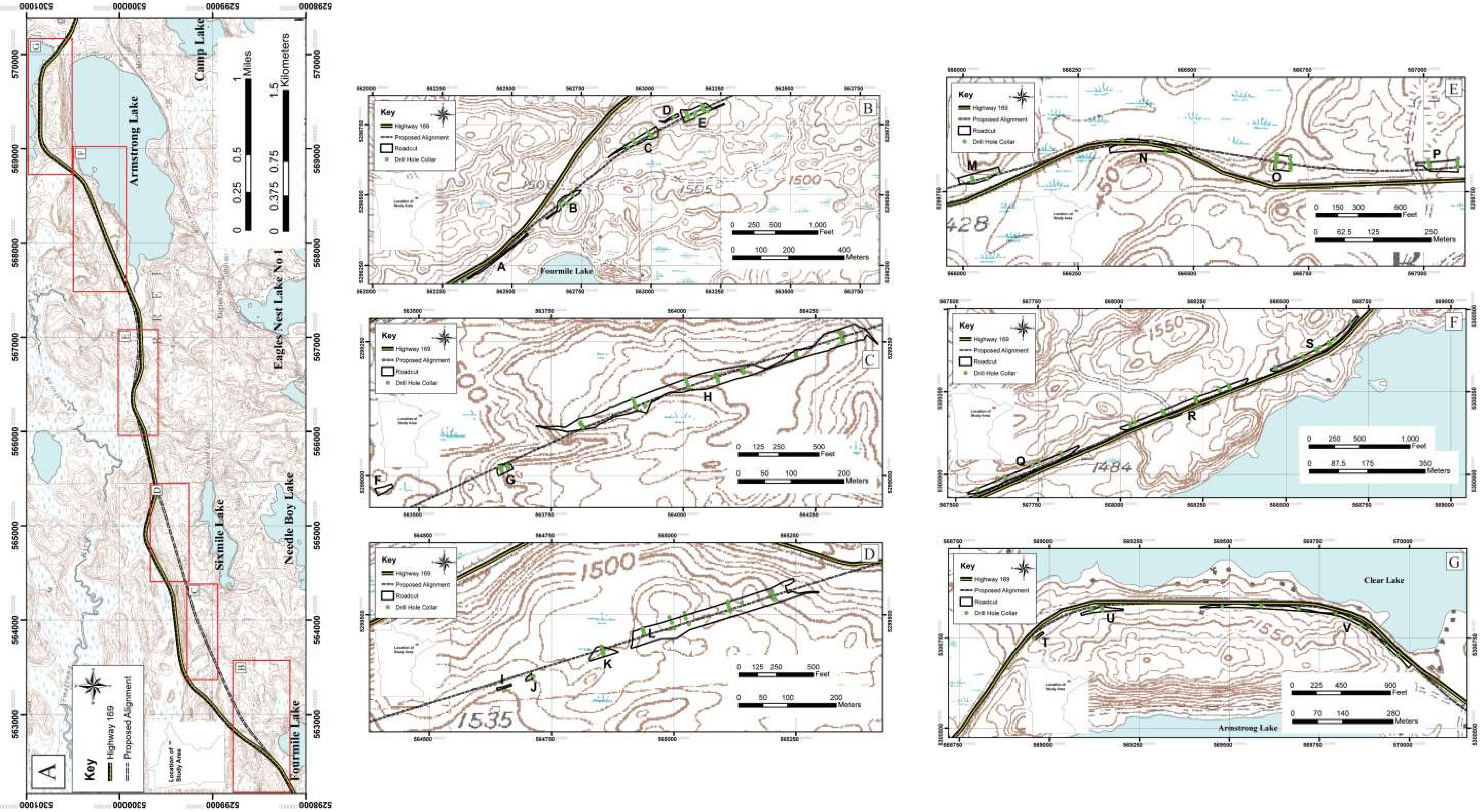

Figure 1. Series of topographic maps showing the locations of the existing Highway 169 and the proposed route with individual roadcuts and drill hole locations: (A) Overview of project area. (B) Roadcuts A-E. (C) Roadcuts F-H. (D) Roadcuts I-L. (E) Roadcuts M-P. (F) Roadcuts Q-S. (G) Roadcuts T-V.

METHODS

Field Methods

Drill hole locations were originally determined by MnDOT to satisfy the sampling agreement developed by MnDOT and the Minnesota DNR. Roadcuts requiring excavation of more than 500 cubic yards of material required drilling across the entire width of the roadcut and at least five feet below the planned excavation depth. This was done to acquire representative lithology information and sulfur content for that particular planned section of highway. Additional holes were drilled based on geophysical induced polarization (IP) anomalies (survey conducted by Golder Associates) and known locations of elevated sulfur content identified by detailed geological mapping (Heine and Severson, 2010; 2012). Planned roadcuts with recommended drill hole locations are shown in Figure 1. Photographs were taken of the sites (preclearing, cleared, and post-drilling) during set up and drilling, and of individual drill core boxes as a record of the work done at each site. Drill hole locations were surveyed by MnDOT during the course of the project.

Once drill hole locations were staked by MnDOT surveyors and the appropriate land access permissions granted, the drill hole lines were flagged and/or a thick stake was driven into the base of one of the drill hole markers so that any markers knocked down during clearing could be replaced while maintaining the correct azimuth and spacing along the drill hole line. The drill sites were then cleared of trees and underbrush. Drill hole lengths were also recalculated to ensure overlap both prior to drilling and with each sequential hole drilled (Figure 2).

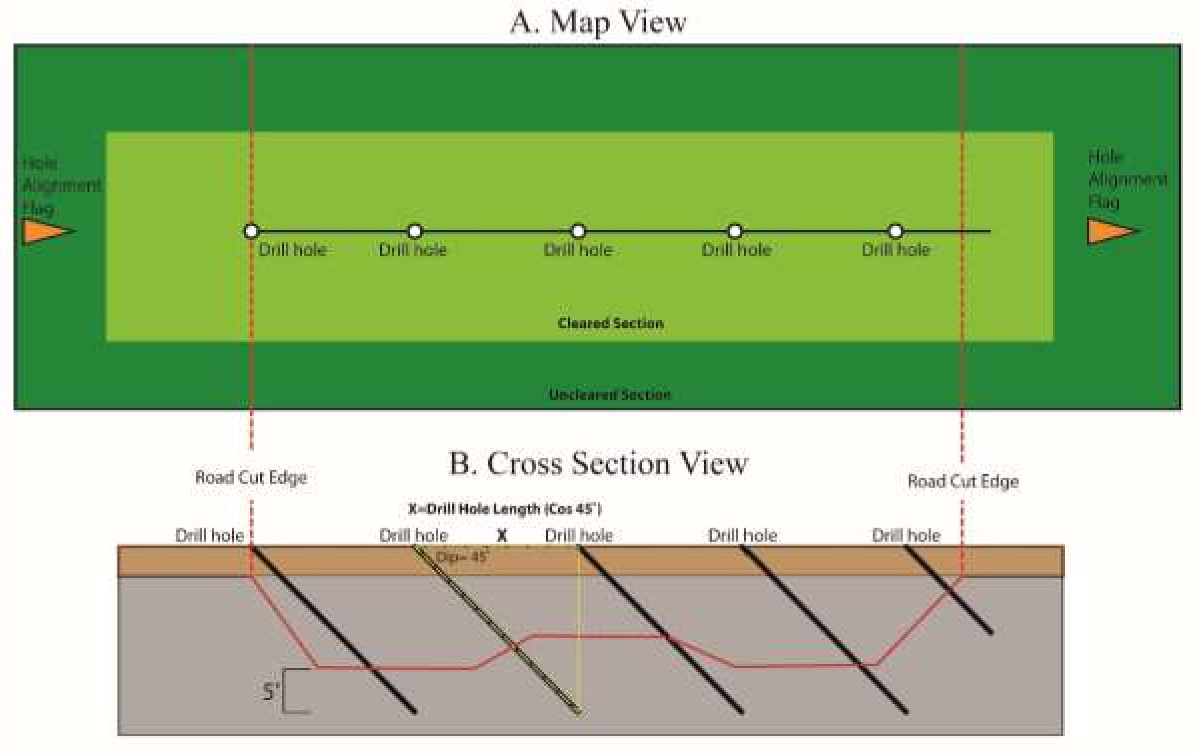

Figure 2. Idealized schematic diagram of a drilling site, where orientation of the alignment is determined to be perpendicular to bedding. Plan (A) and cross section (B) views of typical drill hole arrays.

A number of NQ drill holes were drilled in linear arrays (drill hole lines) across outcrops for this investigation. The number of holes varied in each array, depending on the width and depth of the roadcut, to capture the geological information to a depth no greater than five feet below the depth of the roadcut. The drill hole lines were designed to cross-cut the roadcuts perpendicularly to sample all available stratigraphy to ensure representative sampling of the whole cut. Prior field studies determined that sulfide-bearing minerals, predominantly pyrite, locally occurred in concentrations greater than 1% along bedding planes or in veins in the Soudan Iron Formation (Heine and Severson, 2010; 2012). Drill hole lines were readjusted if the planned lines failed to intersect portions of stratigraphy perpendicular to bedding (dictated by the untested zones of the Soudan Iron Formation).

Drill hole realignment based on the strike of bedding in the Soudan Iron Formation took place only if the outcrops adjacent the drill hole line possessed a relatively uniform strike (determined via sun compass). The goal was to drill the holes as close to perpendicular to bedding as possible. If a uniform bedding orientation could be determined, a staked line running parallel to bedding (parallel to the formation's strike) from the outcrop to the drill hole line was laid out (Figure 3). A second line was set up along the planned drill hole line, and the angle was measured with a digital angle finder. The drill hole line was adjusted when the angle adjustment was greater than 10° from perpendicular to bedding; however, realignment was rarely required, as the preplanned lines took into account the general strike determined from previous field studies.

In some locations (e.g., Roadcut S), bedding was highly variable and required drilling additional drill holes (i.e., BH150 – BH150C). Individual drill holes were locally moved due to inaccessibility issues or the inability to safely drill in some locations. These drill holes were kept as close as possible to their planned location and moved perpendicular to the hole line (parallel to strike) to maintain the same sampling interval. Horizontal holes were drilled in selected locations where the preplanned drill hole locations were on inaccessible hillsides, and sometimes replaced multiple holes (e.g., BH69 replaced the original BH69 in addition to BH70).

Once the drill rig was correctly aligned and leveled, the drilling angle was measured via a digital angle finder or a Brunton compass. As drilling was taking place, a geologist oversaw the placement of core into the core boxes. The core was allowed to air dry. Core tents were assembled on rainy days to ensure that no excess water came in contact with the core.

Upon reaching the targeted drilling depth, a water level reading was taken by an NRRI geologist using an electronic piezometer provided by MnDOT. The object of this test was to determine the groundwater elevation. However, it became apparent that water in the hole was often from the drilling process itself and only stabilized after falling to a depth below major fractures in the bedrock (as seen in the drill core). These measurements could take hours to stabilize if the rock was relatively coherent. Several holes were left unsealed overnight and had water levels that continued to decrease for 12-24 hours after cessation of the drilling. Two methods were utilized to determine the groundwater elevation during this investigation:

1. The original method (Method 1: one measurement after water "stabilized") was abandoned because it was clear that the actual groundwater level was not being measured; rather, it was the rate at which water drained from the hole.
2. A new method (Method 2: three measurements over the course of a half hour (Appendix A) introduced tighter measurement constraints used to calculate water drainage rates.

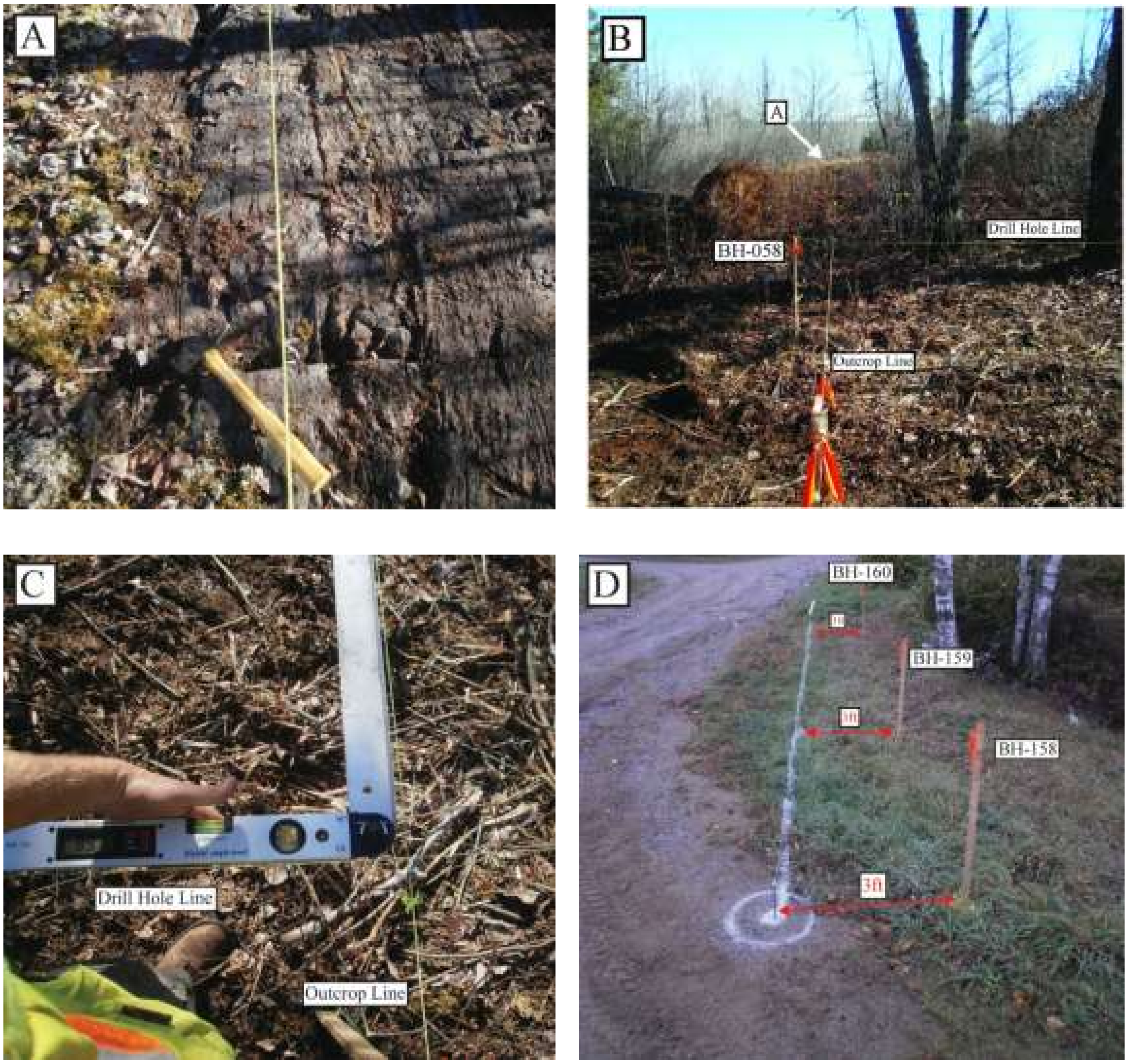

Figure 3. Photographs documenting drill hole realignment: (A) Representative iron formation outcrop with distinct bedding. (B) Drill site line for drill holes BH057 – BH061. Drill hole and outcrop lines with location of outcrop from Figure 3A shown. (C) Angle measurement of the outcrop and drill hole lines. (D) Hole line relocation. The original drill hole line indicated a planned drill hole on the edge of a raised driveway. Drill holes BH158 and 159 were moved three feet east; drill hole BH-160 was moved an additional five feet east (total of eight feet east of original location).

The geologist on site was responsible for filling out drill core logs, noting lithology, alteration, rock properties, and percentage recovered (Quick Log and an NRRI Log, Appendix B and Appendix C). All holes were cemented, staked, and photographed (Appendix D) upon completion consistent with Minnesota Department of Health drill hole abandonment rules. At the end of each day, the drill core was transported to a secure trailer before it was transported to the NRRI Coleraine Laboratory (CL) by Idea Drilling.

DRILL CORE LOGGING AND SAMPLING PROCEDURES

Idea Drilling delivered drill core twice a week to the NRRI CL for logging and sampling. Logging priorities for the project were lithology, alteration, and sulfide mineral content. Rock Quality Data (RQD) was collected and is shown in Appendix C, which contains scans of the MnDOT drill logs. Appendix F contains a summary spreadsheet of those logs. Appendix G contains photos of the drill core and an explanation indicating the drill core photo file naming protocol.

Sample intervals were chosen based first on lithology and then on sulfide content. A sample interval of five feet or less was required by MnDOT. Lithologic intervals less than five feet were laid out as one sample; greater than five feet were divided into one or more sample intervals. The sample intervals were marked with cards identifying the footage of the intervals for cutting (Appendix G) and the core aligned and marked with yellow wax pencil for cutting. A sample list was provided to the cutting personnel with the footage intervals for each sample based on the footage card placed along the core. Samples were cut by CL personnel on diamond-bladed masonry saws, double bagged with sample number tags in each bag, and sealed with tags indicating the sample number. The samples were shipped to ALS Minerals, Thunder Bay, Ont. in fourteen 55-gallon drums for sample preparation and geochemical testing.

Classification Schemes

Rock types are classified using various rock classification schemes during this study. Igneous rock compositions are consistent with LeBas and Streckheisen (1991). Volcaniclastic rocks have been classified in a manner consistent with Fisher (1961) and Fisher (1966). The bedding thickness classification used in drill hole logging is given in Table 1.

Table 1. Bedding classification scheme utilized in the project, after McPhie et al., 1993).

Bedding Type	Bed Thickness (cm)
Laminated	<1
Very thinly bedded	1-3
Thinly bedded	3-10
Medium bedded	10-30
Thickly bedded	30-100
Very thickly bedded	>100

GEOLOGY

The MnDOT Eagles Nest project crosses Neoarchean (~2.7-billion-year-old) bedrock of the Ely Greenstone Formation of the Vermilion Greenstone Belt (Schulz, 1980). Supracrustal rocks encountered during the drilling program, from oldest to youngest rocks, include Lower Ely Member basalt lava flows, Lower Ely Member basaltic volcaniclastic rocks, and the Soudan Member banded iron formation and associated basalt lava flows and volcaniclastic rocks. Intrusive rocks identified during the drilling program include diabase sills and/or dikes and porphyritic dacitic intrusive rocks. Bedrock is overlain by a thin veneer of glaciogenic deposits. Bedrock geology for the drilled roadcuts throughout the project area is presented in Appendix L (Plate 1) and Figure through Figure 9.

Minor modifications to naming convention have been made in this report. The Altered Unit (Alt Unit; Severson and Heine, 2012) is no longer considered a rock type but an alteration type which can be found in Soudan Member Iron Formation as well as Lower Ely Member and Soudan Member Iron Formation basalt lava flows and basalt volcaniclastic rocks. Previous NRRI reports (TR-2010/31 and TR-2012/20) have segregated the Alt Unit as a unique rock type. It consists of thin- to massive-bedded mafic volcaniclastic rocks varying from tuffs to lapilli tuffs to tuff-breccias, as well as Soudan Member banded iron formation that have been subjected to local, moderate to strong alteration comprising a mineral assemblage of epidote, sericite, chlorite, quartz (silicification), and locally, garnet (Severson and Heine, 2012). Pyrite with trace chalcopyrite and/or sphalerite can also occur within this alteration assemblage.

In this report, and specifically on the maps and stratigraphic columns, the Altered Unit is no longer indicated as a separate lithology. It is now interpreted as an alteration assemblage modifying other rock types. Observations of alteration during drill core logging are noted below in the site-specific description of each rock type.

Geological Material Descriptions

Overburden

Regional Description

Late Pleistocene glacial deposits (Late-Wisconsin glaciation) in the region are associated with the stepwise retreat of the Rainy Lobe of the Laurentide Ice Sheet, approximately 14,000 to 12,000 years ago (Lehr and Hobbs, 1992). The repeated glaciations of the Pleistocene epoch modified the pre-existing topography of northeastern Minnesota, i.e., the surface was scoured by glacial ice, exposing fresh bedrock, and new surficial materials were deposited following the retreat of the glaciers. During the retreat of the glacier, the margin of the ice-sheet blocked the natural drainage to the north, and pro-glacial lakes formed in front of this barrier (glacial lakes Norwood, Koochiching, and Agassiz). Subglacial streams left sinuous ridges of sorted sand and gravel (eskers), and delta/fan complexes formed where these streams exited the ice margin and entered the pro-glacial lakes.

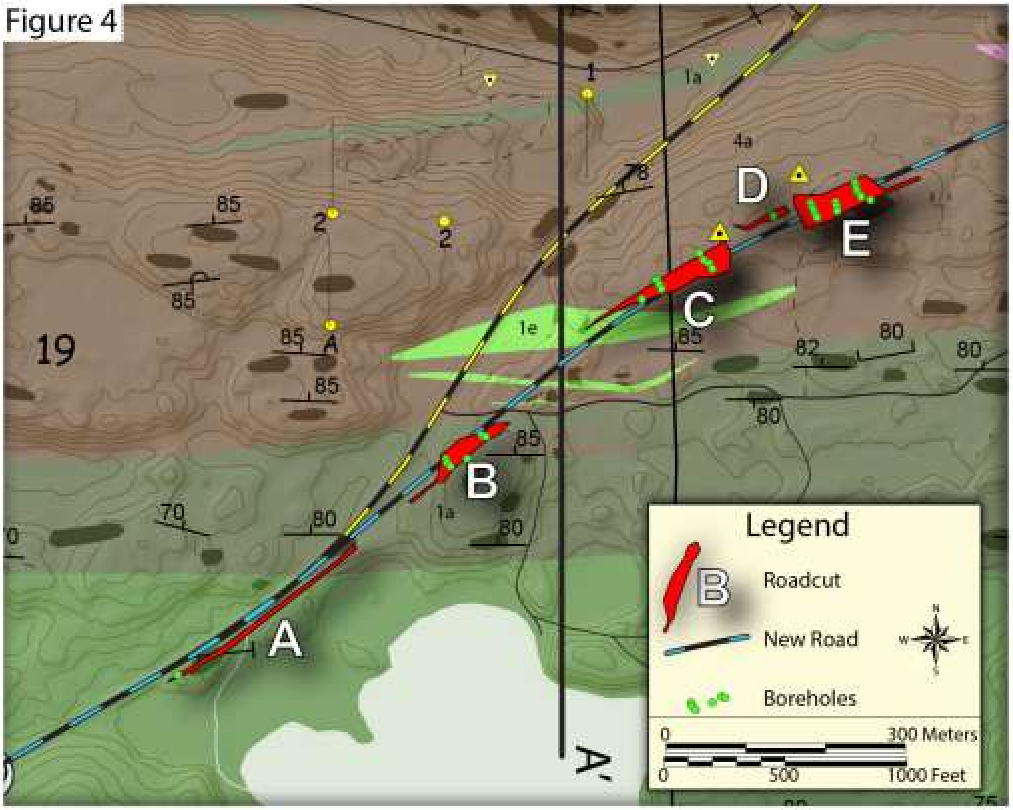

Figure 4. Bedrock geology of Roadcuts A-F. Grid coordinates in UTM, NAD83.

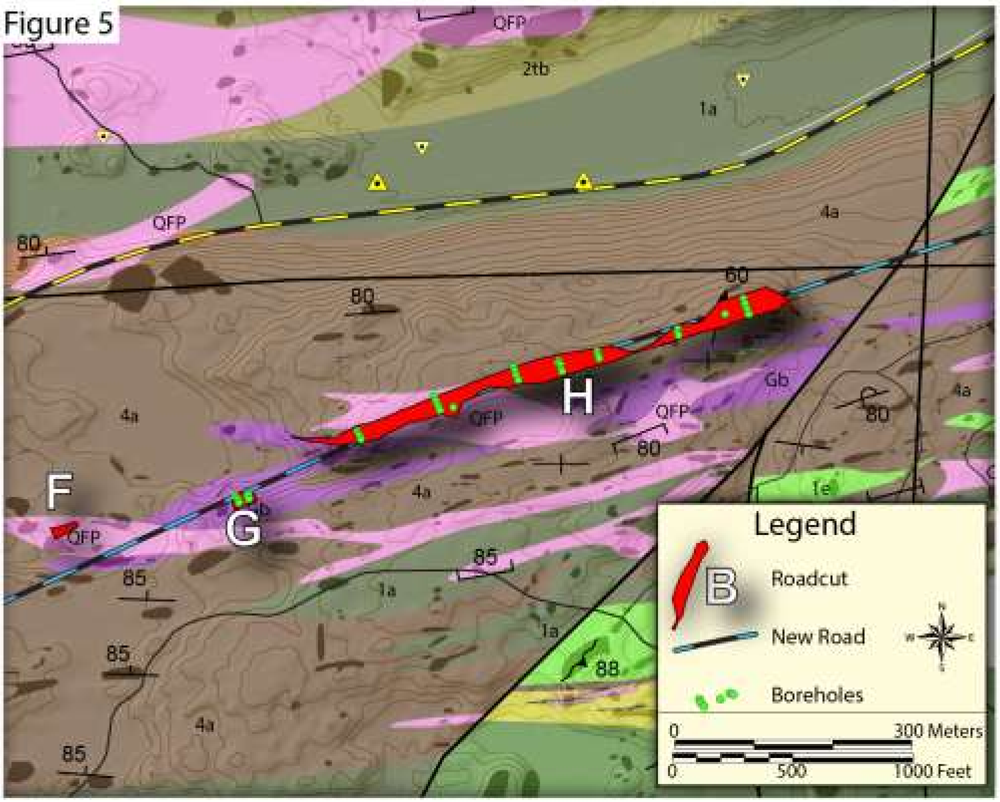

Figure 5. Bedrock geology of Roadcuts F-H. Grid coordinates in UTM, NAD83.

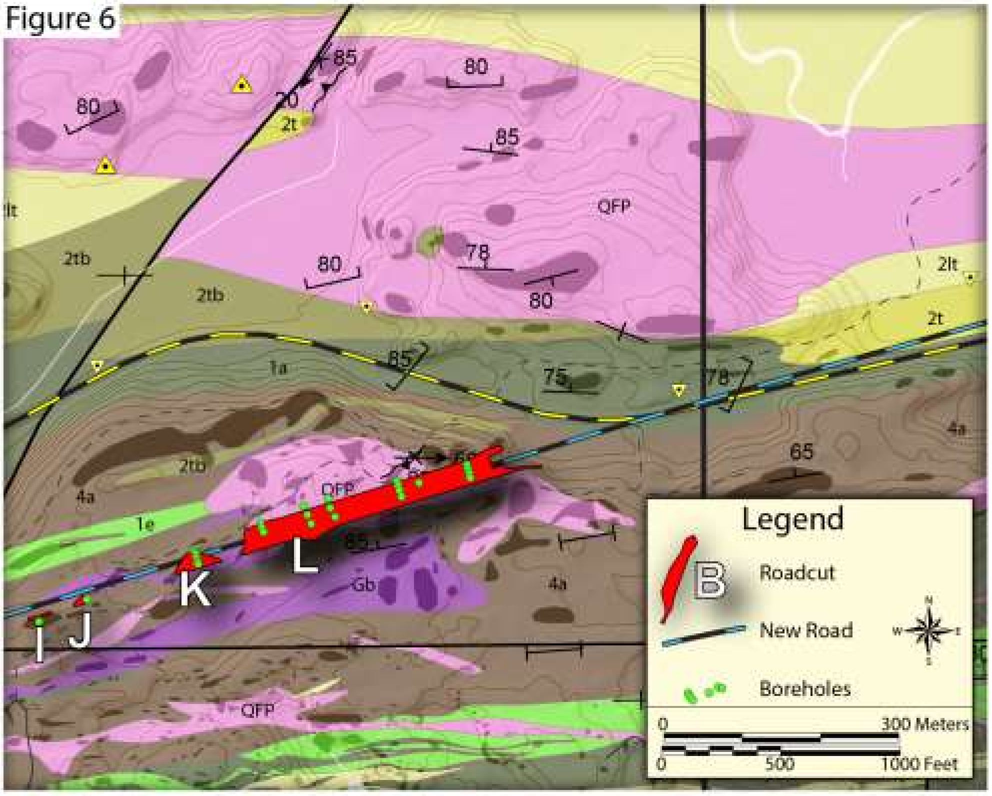

Figure 6. Bedrock geology of Roadcuts I-L. Grid coordinates in UTM, NAD83.

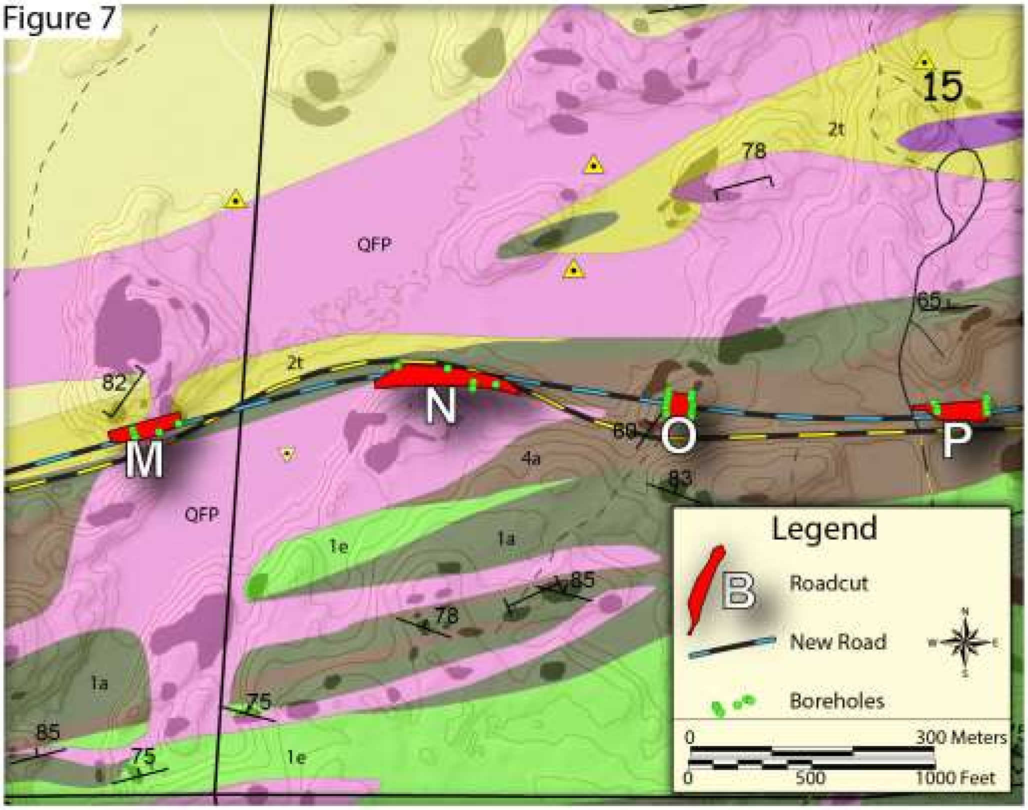

Figure 7. Bedrock geology of Roadcuts M-P. Grid coordinates in UTM, NAD83.

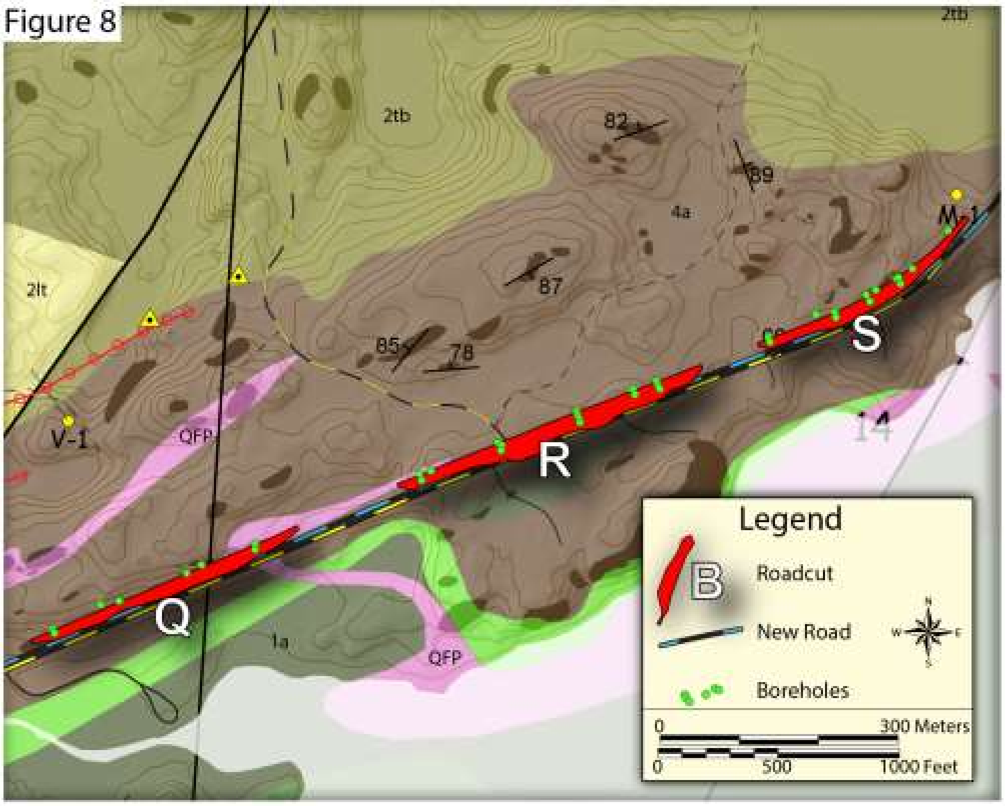

Figure 8. Bedrock geology of Roadcuts Q-S. Grid coordinates in UTM, NAD83.

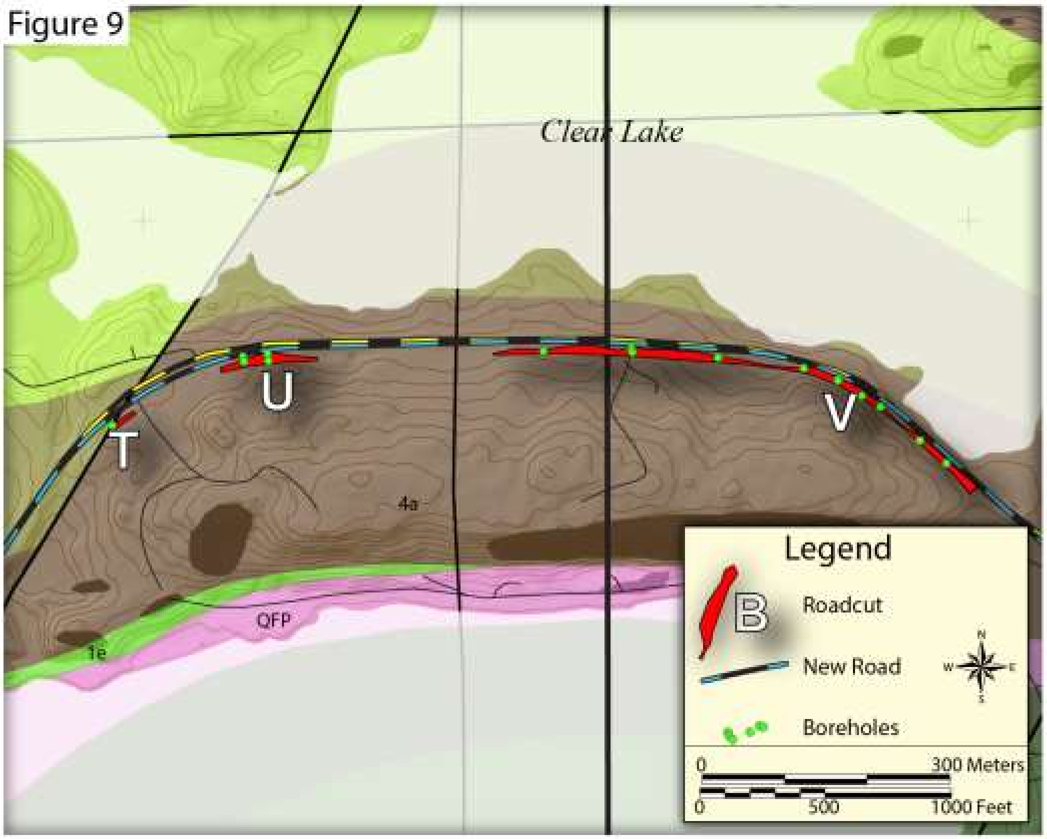

Figure 9. Bedrock geology of Roadcuts T-V. Grid coordinates in UTM, NAD83.

Surficial deposits covering much of the bedrock in the immediate field area include glacial deposits related to the ~12,500-year-old margin of the Laurentide ice sheet (ice margin defined by the location of the Vermilion Moraine) and the recent Holocene (<10,000-year-old) soils and forested peat bogs. Glacial deposits include a thin veneer of basal till, erratics, melt-out boulder lag deposits, and steep-sided ridges of subglacial fluvial deposits (eskers) on the scoured bedrock uplands north of the moraine.

Site-Specific Description

The drilling method is not conducive to sampling overburden (OVB); core drilling with water tends to wash most of the clay, silt, and sand fractions of the material away. Recoveries of the OVB are in the 5% to 15% range and typically included pebbles, cobbles, and drilled boulder materials.

OVB thicknesses range from 0 – 75.9 feet in the drill holes completed for the Eagles Nest project along Highway 169. Based on the drill core observations, overburden is encountered from ground surface to the base of the Roadcuts C, G, O, P, R, and U as seen in the cross sections (Appendix I). Overburden is absent in some of the drill holes completed in Roadcuts L, N, and S.

In the core samples, overburden sediment grain size ranges from silts/clays to boulders, with pebble and gravel size materials dominant (Table 2). The observed grain size of the sediment in drill core has likely been skewed due to the drilling process, where fine-grained sediment is washed away and not recovered in the core tube. Rock types observed in the coarse fraction (pebble-gravel size) of the core samples included iron formation and igneous rocks of the composition of dacite, diabase, granite, and basalt (Figure 10).

Table 2. Wentworth scale of grain size.

Class Name	Size Range (metric)
Boulder	> 256 mm
Cobble	64 - 256 mm
Gravel	2 - 64 mm
Sand – Coarse	0.5 - 2 mm
Sand – Medium	0.25 - 0.5 mm
Sand – Fine	125 - 250 µm
Sand – Very Fine	62.5 - 125 µm
Silt	3.9 - 62.5 µm
Clay	0.98 - 3.9 µm

Figure 10. Overburden recovered from drill hole BH_010, interval 0 – 31 feet, Roadcut C.

Supracrustal Rocks

Soudan Member Banded Iron Formation

Regional Description

The Soudan Iron Formation (SIF) is composed of black to gray, thinly laminated beds of magnetite-hematite interlayed with gray chert and minor red jasper beds. Lesser, primary mafic lava flows and primary and resedimented mafic tuffs, mafic lapilli tuffs, and mafic tuff breccias are locally interlayered with the banded iron formation (Heine, 2015). In the western part of the field area, dacite sills locally intrude into the banded iron formation. The banded iron formations formed during a period of relative volcanic quiescence dominated by chemical sedimentation and a stratigraphic thickness of up to 600 meters of iron formation can be encountered in the project area.

Site-Specific Description

In general, banded iron formation observed in drill core (Figure 11) include thinly laminated beds of magnetite-hematite interlayed with gray chert and minor red jasper beds. Bedding features interpreted as results of soft sediment deformation include convolute, broken, and disrupted bedding. SIF is encountered in 90 of the drill holes, and thicknesses range from 0.1 m to 13 m, with an average 5 m. As seen on the bedrock maps (Figures 4-9), road construction will encounter SIF in Roadcuts C, E, D, G, H, K, I, L, O, Q, R, S, T, and V.

Alteration minerals observed in the SIF consist most frequently of quartz, carbonate, and chlorite, with sericite and garnet present in some cores. SIF with alteration is present in Roadcuts D, E, H, I, L, Q, R, and S (Appendix I). Veins and fractures are common in SIF and contain some or all of the following minerals: quartz, carbonate, epidote, pyrite, and garnet. Veining tends to range in thickness from less than 0.5 mm to 15 mm, with the majority between 0.5 mm to 5 mm. Spacing between veins is irregular, with spacing ranging between 15 mm to 30 cm. Fracture thicknesses range from less than 1 mm to 3 mm, with irregular spacing from 2.5 cm to 30.5 cm.

Pyrite occurs locally as disseminated grains throughout the rock as well as within fractures, veins, and subparallel to bedding. Individual recrystallized pyrite cubes range in size from less than 1 mm to 4 mm in the SIF, with visually estimated pyrite content ranging from trace to 20% in drill core. The majority (63%) of the visually estimated sulfide content observed in core is 1% or less (Figure 12). The total sulfur content in the SIF samples is determined by Leco Sulfur analyses, which ranges between 0.1% and 11% total sulfur, with approximately 65% of the samples containing ≤0.25% sulfur (Figure 12).

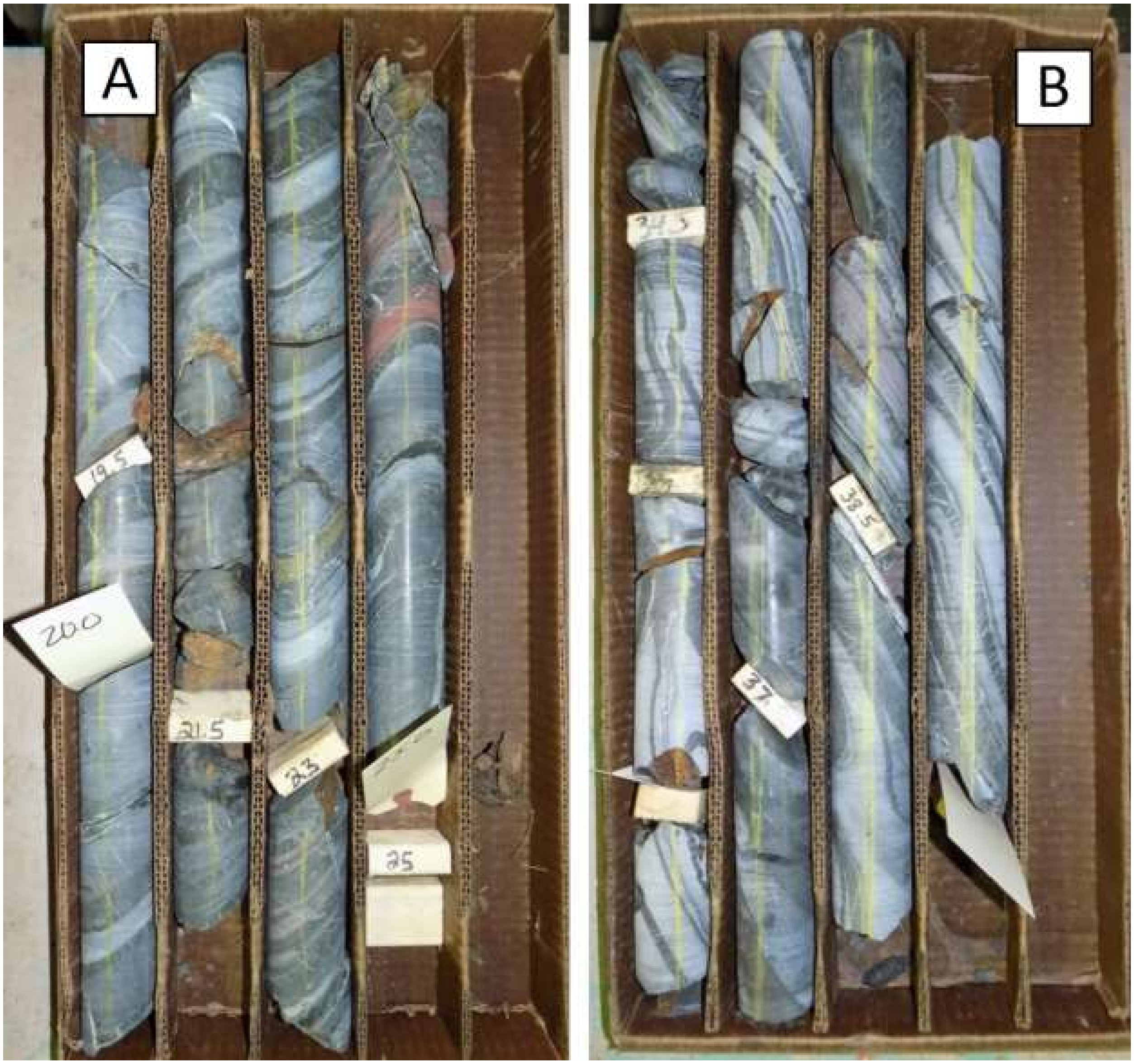

Figure 11. Soudan Iron Formation drill core: (A) Drill hole BH-052, interval 19' – 25', Roadcut H. Note red jasper beds, tension gashes, fractures, and local bedding parallel pyrite. (B) Drill hole BH-168, interval 34.5' – 40.5', Roadcut V. Note the semi-convoluted bedding, broken and offset bedding, tension gashes, veining, and fractures.

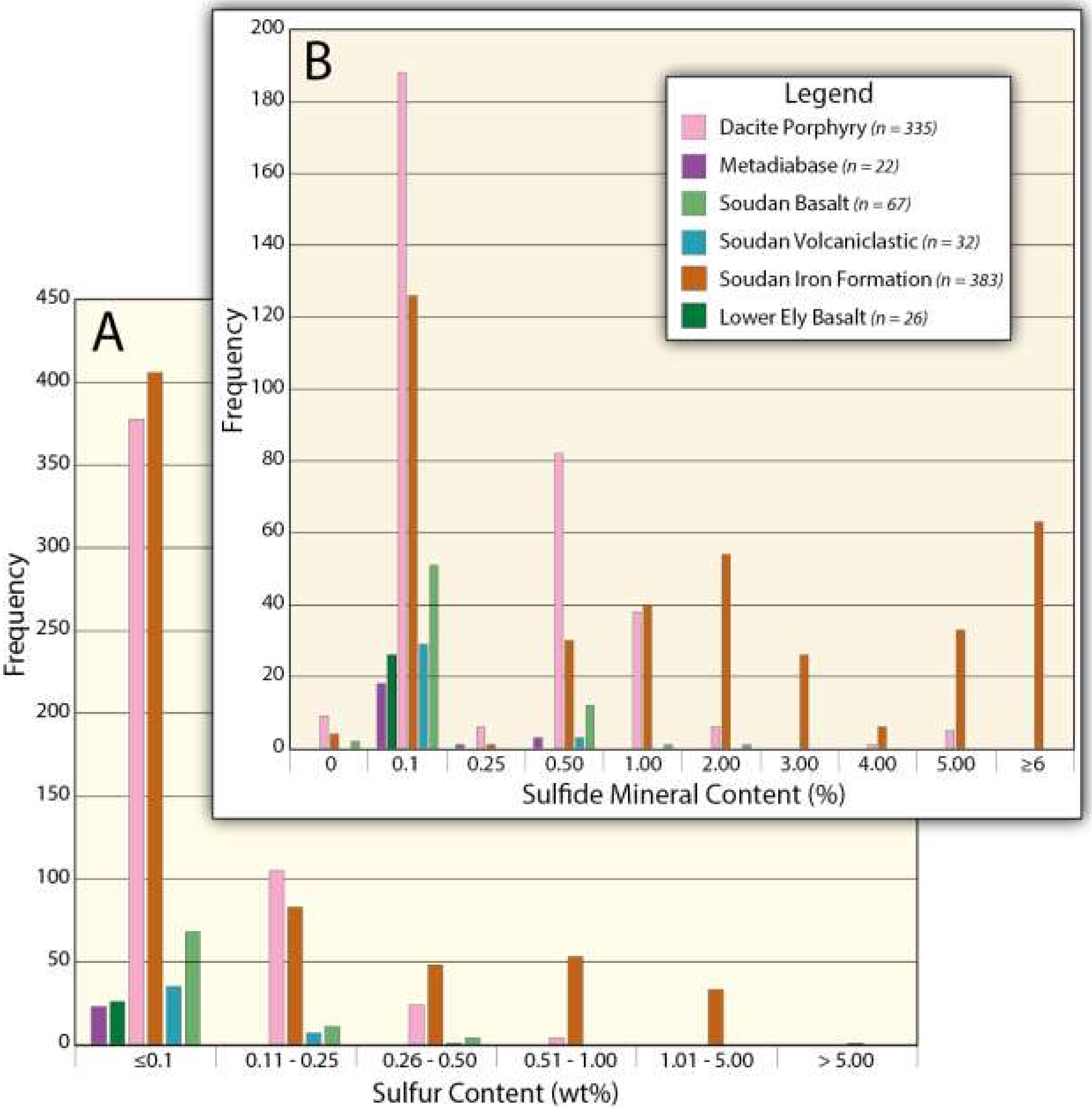

Figure 12. Geochemical and mineralogical histograms of the six major rock units identified during the drilling project. (A) Distribution of total weight percent sulfur as determined by ALS Minerals. (B) Visually estimated sulfide content of all drill core samples.

Soudan Member Mafic Volcanic and Volcaniclastic Rocks

Regional Description

The Soudan Iron Formation, which dominantly consists of laminated Algoma-type iron-formation, also contains interbedded basalt lava flows and volcaniclastic rocks of basaltic to dacitic composition. In general, the bedding characteristics of many of the rocks of the Soudan Iron Formation are interpreted to represent deposition from deep-water chemical deposition from exhalation of hydrothermal fluids on the Neoarchean seafloor during a period of volcanic quiescence, which began during the latest stages of volcanism associated with the Lower Member of the Ely Greenstone and continued after cessation of Lower Member volcanism. A gradational contact over several tens to hundreds of meters occurs between the underlying Lower Ely and the overlying Soudan Iron Formation (Hudak et al., 2007). The upper contact of the Soudan Iron Formation member has been interpreted as an unconformity (Lodge et al., 2013), and the relationships between apparent overlying stratigraphic units (Upper Member of the Ely Greenstone Formation, the Gafvert Lake sequence, and the Lake Vermilion Formation (Peterson and Patelke, 2003) remain poorly understood.

Site-Specific Description

Mafic volcanic (Figure 13) and volcaniclastic (Figure 14) rocks are gray/green and pink, fine- to very-fine grained, and are present in nine of the drill holes. Bedding ranges from massive to thin- or medium-thick beds that are locally folded. Stratigraphic thicknesses range from ~2 – 8.5 meters. Road construction will encounter Soudan basalt and volcaniclastic rocks in Roadcuts C, H, L, and Q (Figures 4, 5, 6, and 8). Alteration in these units is locally well developed (especially in drill cores in Roadcuts C and H) with alteration mineralogy including quartz, chlorite, iron carbonate, epidote, and sericite.

Veins and fractures in basalt and volcaniclastic rocks contain some or all of the following minerals: quartz, carbonate, and hematite. The irregularly spaced veins range in thickness from less than 1 mm to 13 mm, with spacing ranging from 15 to 37 cm apart. Fracture thicknesses range from less than 1 mm to 3 mm, with spacing also tending to be irregular but ranging from 2.5 cm to 31 cm.

Pyrite occurs as disseminated recrystallized cubes as well as in fractures, veins, and/or bedding planes. Cubic pyrite ranges in size from less than 1 mm to 4 mm. Sulfide mineralization is estimated to range from 0.25% to 8% within these rocks. During core logging, 0.5% or less sulfides were observed in 87% of the core (Figure 12). Lithogeochemical analyses appear to support the observed sulfide mineral frequency, with approximately 87% of the samples containing Leco sulfur levels at or below 0.25 % (Figure 12).

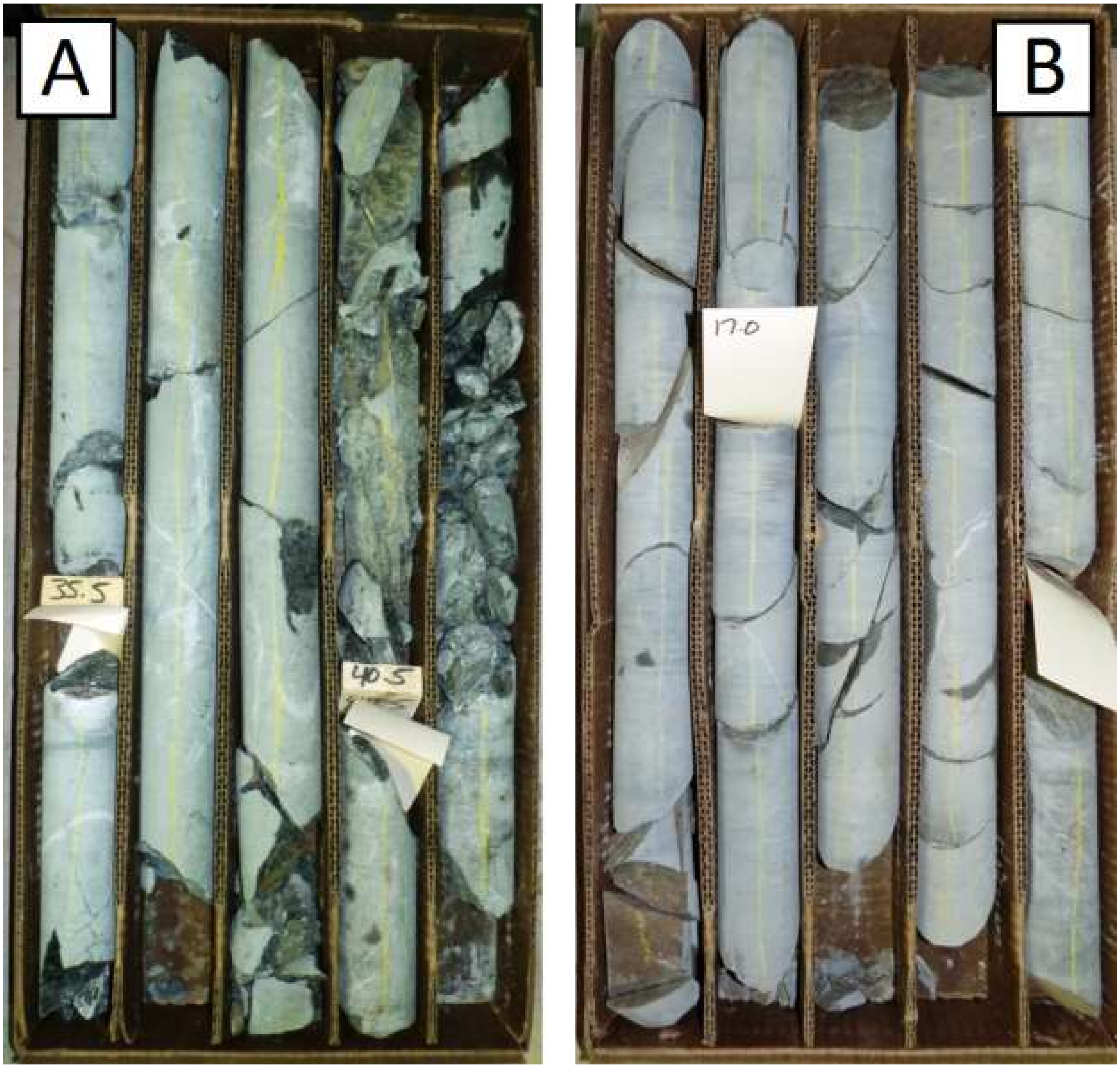

Figure 13. Soudan Member basalt lava flow drill core: (A) Drill hole BH-150B, interval 34.5 – 43, Roadcut S. Note veining, fracturing, and shearing (~40.5). Note that vein fill includes quartz, carbonate, epidote, and chlorite with disseminated pyrite. (B) Drill hole BH-130, interval 15 – 22.5, Roadcut R. Note veining, fracturing, and weak alteration. Vein and fracture fills include quartz, carbonate, and hematite with disseminated pyrite. Alteration minerals include quartz, carbonate, chlorite, and hematite.

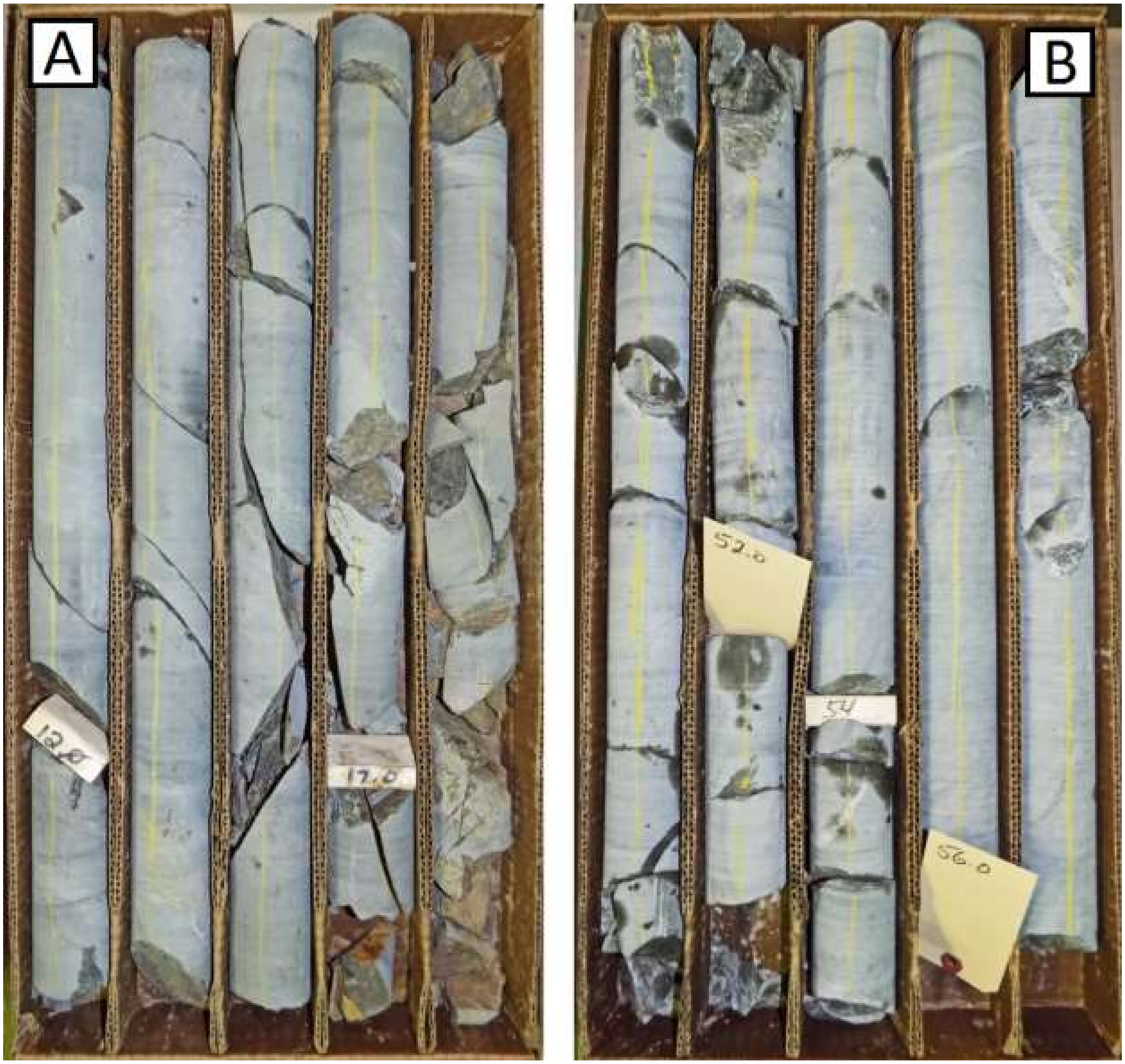

Figure 14. Soudan Member mafic volcaniclastic rocks in drill core: (A) Drill hole BH-041, interval 11 – 32 feet, Roadcut H. Rock is weakly altered and contains trace disseminated pyrite, veining, and fractures. (B) Drill hole BH-071, interval 49.5 – 57.5, Roadcut L. Note massive to diffuse bedding, veining, fractures, and trace amounts of disseminated pyrite.

Lower Ely Member Basalt Lava Flows

Regional Description

The Lower Member of the Ely Greenstone Formation consists dominantly of pillowed and massive basalt and andesite flows of calc-alkalic and tholeiitic composition (Hudak and Peterson, 2014). Hypabyssal diabase, gabbro, and dioritic sills, isolated dacitic, rhyodacitic and rhyolitic lava flows and domes, and local volcaniclastic rocks occur throughout the sequence. The uppermost pillowed basaltic rocks of the Lower Ely Member are typically non-vesiculated to sparsely vesiculated. This, combined with the lack of primary volcaniclastic deposits (e.g., scoria-rich tuffs and lapilli-tuffs) within this stratigraphic unit, has led to the interpretation that these lava flows were formed during subsidence of the volcanic pile to deep-water conditions (Schulz, 1980; Hudak et al., 2007; Hudak et al., 2012). The Lower Ely basalts occur in Roadcuts A and B (Figure); all other basaltic rocks intersected by drilling are interbedded within the Soudan Iron Formation and are classified as Soudan basalt.

Site-Specific Description

Basalt lava flows observed in drill core are green gray, very fine- to medium-grained, slightly foliated, massive to sparsely amygdaloidal, and are interpreted as massive sheet flows. The Lower Ely Member basalt lava flows are identified, at least in part, by stratigraphic position (e.g., always occurring in the footwall to the Soudan Member). Veining, fracturing, and tension gashes are commonly noted in the core, and contacts with the iron-formation locally are sheared and foliated. Moderate to strong epidote-bearing alteration is locally observed in Roadcuts A and B. Altered basalt is present in Roadcuts A and B. Veins in the basalt range in thickness from less than 1 mm to 2.5 cm and contain quartz, chlorite, and carbonate (Appendix I). Spacing of veins varies between 13 mm and 31 cm. Fractures ranging from less than 1 mm to 3 mm in thicknesses commonly contain quartz, carbonate, and hematite. Spacing between the fractures varies from 13 mm to 25 cm and are irregular.

Pyrite occurs as disseminations as well as fracture fillings. Cubic pyrite ranges in size from less than 1 mm to 3 mm and ranges in concentration from trace to 7% (weighted average of 0.3%). Concentration by visual estimates ranges from trace to 2%, with weighted averages ranging from 0.001% to 0.8% in the basalts. Approximately 96% of the basalts are observed to contain 1% or less visible sulfides (Figure 12A). Leco sulfur results also indicate a low concentration of sulfur, with about 94% of the samples containing 0.25% sulfur or less (Figure 12B).

Intrusive Rocks

Dacite Sills and Dikes

Regional Description

Dacitic quartz-feldspar porphyry (QFP) intrusions are white to whitish-pink, medium-grained intrusive rocks with sub-rounded white feldspar and clear to white quartz phenocrysts in a fine-grained quartzo-feldspathic + mafic groundmass. The original mafic component (5% to 15%) appears to be (or was) hornblende, which is typically pseudomorphed by chlorite, actinolite, and/or epidote. Traces of disseminated pyrite are common. Individual QFP map units are interpreted as both syn-deformational dike-like bodies associated with shear zones (Peterson, 2016; Peterson and Patelke, 2003) and as porphyritic dacitic intrusions associated with the genesis of ~2689 Ma (Lodge et al., 2013; 2015) overlying volcanic rocks of the informally named Gafvert Lake Sequence.

Site Specific Description

Dacite intrusive rocks observed in drill core are gray-green to locally pink and are commonly porphyritic with a very fine- to medium-grained groundmass (Figure 15). Phenocrysts include 20% 1 mm to 8 mm quartz crystals and 15% 1 mm to 6 mm plagioclase crystals. Dacite ranges in apparent stratigraphic thickness from 0.3 m to 21 m and is present in 68 of the drill holes. Both intrusive and fault-bounded contacts are observed between the dacite intrusions and country rocks. Road construction will encounter dacite in Roadcuts B, G, H, K, L, M, N, O, Q, R, S, and V (Figures 4 through 8).

Alteration of the dacite is present in 51 of the drill holes and is characterized by the presence of two or more of the following minerals: quartz, chlorite, iron carbonate, sericite, hematite, epidote, and/or magnetite. Alteration is not observed in core from Roadcuts Q, R, and S (see cross sections, Appendix H).

Veins and fractures in the QFP are filled with various percentages of the following minerals: quartz, carbonate, chlorite, +/- hematite, and +/- pyrite. Veining typically ranges in thickness from less than 0.5 mm to 50 mm. These veins are spaced irregularly in intervals varying from less than 1 cm to 25 cm. Fracture thicknesses range from less than 1 mm to 5 mm and are irregularly spaced from 10 mm to 31 cm.

Pyrite occurs disseminated throughout the rocks as well as in fractures and veins and ranges in diameter from less than 0.5 mm to 4 mm. Pyrite occurs in concentrations ranging from trace to 3%. The weighted average is approximately 0.5%. Visible sulfide minerals are observed at 1% or less in 94% of the dacite containing cores (Figure 12). Leco sulfur analyses are reported to be 0.25% or less in about 92% of the samples (Figure 12).

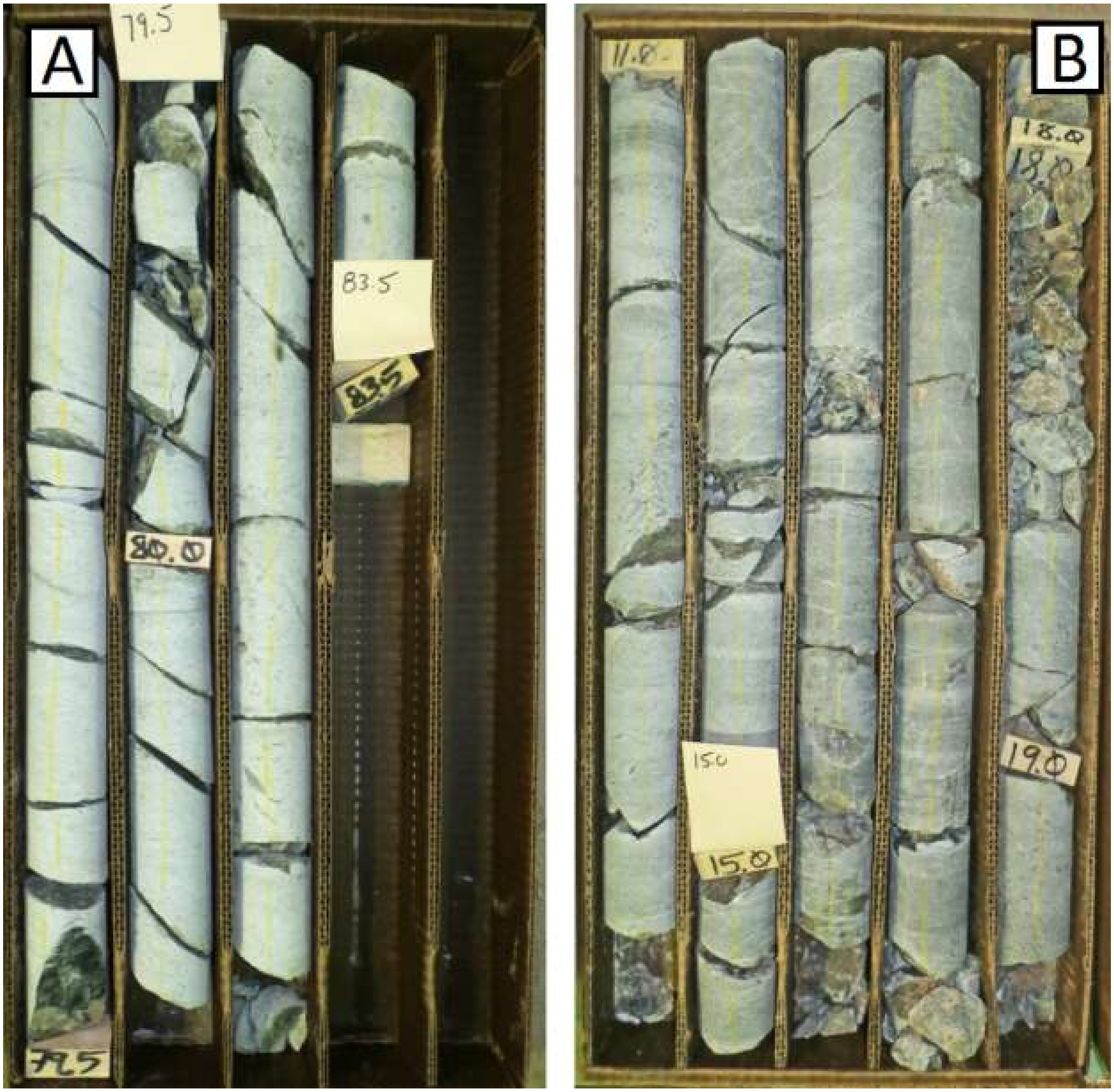

Figure 15. Dacitic quartz-feldspar porphyry intrusive rocks in drill core: (A) Drill hole BH-91A, interval 77.5 – 83.5 ft., Roadcut N. Note the lack of weathering, disseminated pyrite, veining, and fracturing. (B) Drill hole BH-097, interval 11 – 19.5 ft., Roadcut N, weathering, veining, and fracturing.

Diabase

Regional Description

Meta-diabase and meta-gabbroic rocks occur throughout the area as dark green to black, fine- to medium-grained, plagioclase-phyric dikes and sills that are interpreted as feeders (dikes) and hypabyssal magma chambers (sills) to overlying mafic volcanic rocks (Peterson and Patelke, 2003). Thick sill-like bodies locally contain preserved patches of ophitic texture. Thick massive units commonly contain inclusions of the local country rock and were competent during D2 deformation. Thin sills generally have a moderately well-developed east-west fabric but are not strongly foliated. There are rare concentrations of fine-grained pyrite in these rocks, and very fine-grained leucoxene alteration is commonly visible on cut and broken faces. White quartz veins filling brittle fracture arrays are locally common.

Site Specific Description

Diabase sills are identified in 13 of the drill holes across the project corridor (Figure 16) in Roadcuts B, D, E, G, H, Q, and R. At Roadcuts B and R, the top of the diabase will be encountered at the very base of roadcut (Appendix G). Chilled margins, cross-cutting relationships, and fault contacts with slickensides are used to distinguish the dikes from the lava flows. Dike intersections range between 1m to 4.5 m wide. The basalt flows in the Soudan Iron Formation are typically very fine grains to aphanitic.

Diabase intrusives are gray to gray-green, fine- to medium-grained, and are commonly weakly foliated. Either xenoliths and/or inter-fingering of banded iron formation and diabase intrusive rocks are observed locally in the core. Quartz, chlorite, carbonate, +/- epidote zones of alteration are also locally observed in core from Roadcuts B, E, and Q.

Veining is intermittent, with spacing between .03 cm and about 20 cm. The widths of the veins range from less than 0.5 mm to 8 mm. Veins are filled with quartz, iron carbonate, chlorite, epidote, and/or pyrite. Fractures in the rock are less than 1 mm to 8 mm wide and erratically spaced, 2.5 cm to 15 cm. Fracture fill includes quartz, iron carbonate, chlorite, hematite, and pyrite. In some core, slickensides are characterized by the presence of chlorite.

Pyrite occurrs as disseminated recrystallized subhedral to euhedral cubes between less than 1 mm and 3 mm in size, with a trace amount to 0.5%. In the fractures and veins, pyrite cube size ranges between less than 1 mm and 4 mm as a trace -10% of the vein or fracture, with a weighted average of 0.29%. The percent visible sulfide observed during rock core logging in the diabase is consistently less than 0.5% (Figure 12). The results of Leco sulfur analyses produced detection of sulfur at 0.1% or less for 100% of the samples submitted (Figure 12).

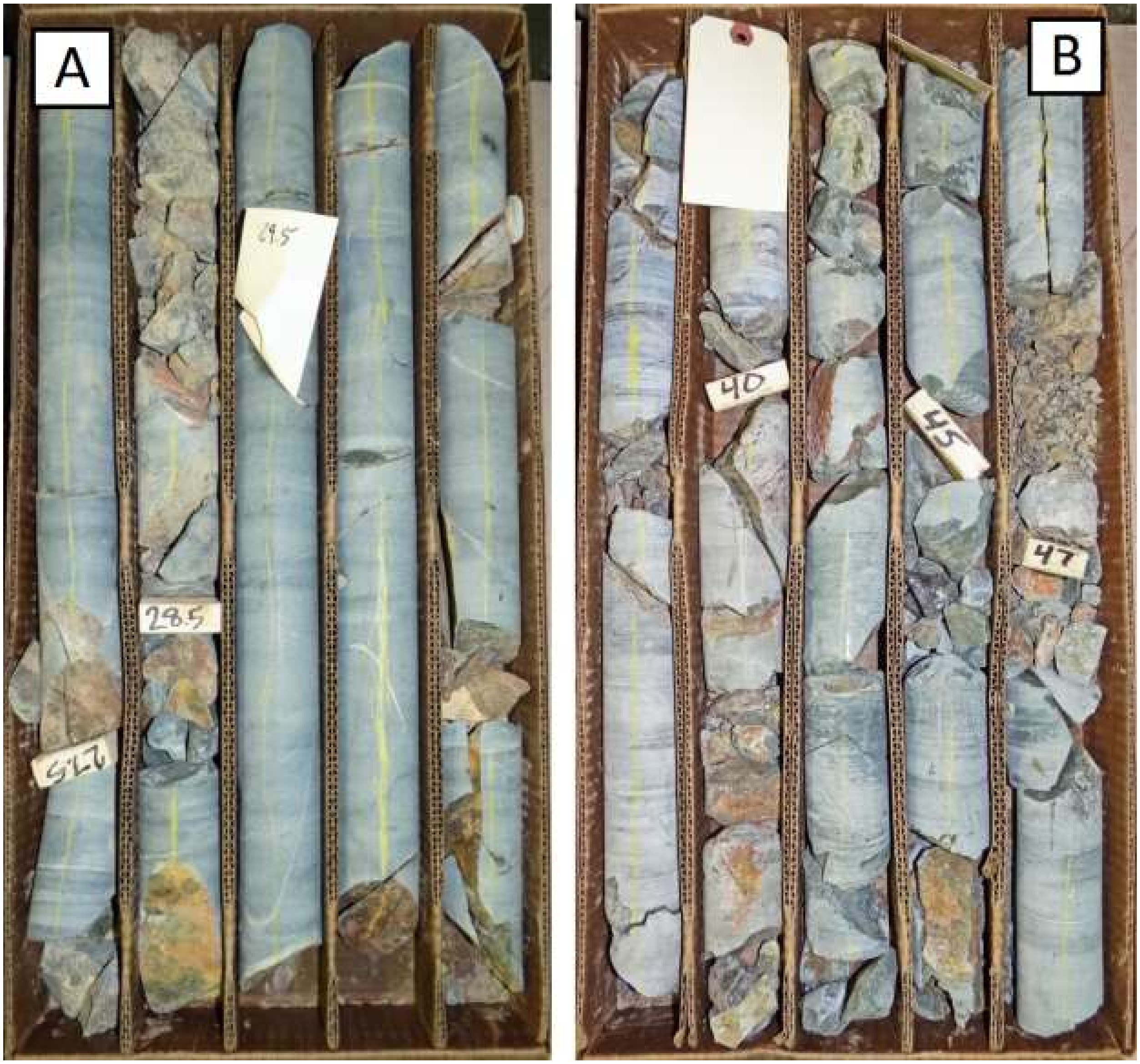

Figure 16. Diabase intrusive rocks in drill core: (A) Drill hole BH-124, interval 26 to 34, Roadcut Q. Note weakly altered with disseminated pyrite, veining, and fracturing. (B) Drill hole BH-125, interval 28' – 48', weakly altered diabase from 39.5' – 48', Roadcut Q. Note the weathering as well as veining and fractures. Vein and fracture fills includes quartz, iron carbonate, +/- epidote, +/- chlorite, and trace disseminated pyrite. Alteration minerals include quartz, carbonate, chlorite, and epidote.

GEOCHEMISTRY

Geochemical analyses for the project were completed by ALS Minerals, Thunder Bay, Ont, Canada. Seven hundred seventy-seven drill hole samples were collected for geochemistry, with 88 samples duplicated for quality assurance. Geochemical standards used to quantify the quality of the results included 40 samples of Canadian Certified Reference Materials Project (CCRMP) standard NBM-1 (a Canadian Certified Reference Material for acid base accounting) and 21 samples of CCRMP standard WMG-1a (a certified reference material for a mineralized gabbro with gold and platinum group elements). ALS Minerals certificates of analyses, quality control certificates, and invoices for this work are found in Appendix J. The geochemistry results are presented in spreadsheet form in Appendix K.

MnDOT and the Highway 169 Technical Working Group requested that geochemical analyses for each sample include acid-base accounting (ABA) (ALS Code: OA-VOLO8ms), paste pH (ALS Code: OA-ELE07), and total sulfur via the Leco method (ALS Code: S-IR08). In addition, samples with greater than 1% sulfur (n = 34 samples) were also analyzed by ICP-MS for 51 trace elements (ALS Code: ME-MS41) to identify elements that may be released from the rocks with the chemical breakdown of sulfide minerals.

Seven hundred seventy-seven samples and 88 duplicates were analyzed for total sulfur as part of the ABA method. One hundred eighty-one samples of Soudan Iron Formation, 90 samples of dacite, 10 samples of basalt, and 3 samples of mafic volcaniclastic sediments were above 0.15% sulfur. Thirty-four samples contained concentrations of sulfur greater than 1%, with the highest concentration of sulfur being 10.6%. All samples with concentrations of total sulfur above 1% are composed of Soudan Iron Formation obtained from Roadcuts E, H, S, T, and V. The samples above 1% sulfur were run for potential metal contents using an ultra-trace metals package using an Aqua Regia digestion using ICP-MS (ALS package ME-MS41).

CONCLUSIONS

The goal of this project was to provide MnDOT the geological data to produce a mitigation plan for the Highway 169 Eagles Nest project. A MnDOT collaboration with the Minnesota DNR and Golder Associates developed the guidelines for this work with the help of the Highway 169 Technical Working Group.

NRRI personnel logged 182 drill holes from the proposed roadcuts located in Highway 169.

The following geological units were encountered in the drilling: Lower Ely Member Basalt lava flows, Soudan Member mafic volcanic and volcaniclastic rocks, dacite intrusive rocks, and Diabase intrusive rocks.

Seven hundred seventy-seven samples and 88 duplicates were analyzed by ALS Laboratories for the following parameters: acid-base accounting and samples above 1% sulfur potential metal contents using an ultra-trace metals package using an Aqua Regia digestion using ICP-MS (ALS package ME-MS41).

Two hundred seventy-four samples had total sulfur concentrations greater than 0.15%, and 34 samples had total sulfur concentrations greater than 1%. All samples containing total sulfur greater than 1% were samples of the Soudan Iron Formation.

The Lower Ely Basalts are massive flows found in Roadcuts A and B only and are quartz-chlorite altered with the former Alt Unit type alteration common. Soudan Iron Formation was the most common rock type encountered in the drilling. It is commonly quartz altered with local Alt Unit type alteration. The Soudan Basalts are fine-grained, massive basalt flows in the Soudan Iron Formation, commonly with quartz-chlorite alteration. The Soudan Mafic volcaniclastic rocks are fine- to medium-grained bedded tuffs; all are quartz-chlorite altered and locally can contain Alt Unit type alteration. Diabase is a fine- to medium-grain, plagioclase-phyric intrusive mafic rock and is a minor component of the rock in the cut areas. Alteration in the diabase is usually pervasive chlorite and quartz, with the addition of epidote locally. Porphyritic dacite is the other major rock type in the roadcuts, composed of quartz and feldspar phenocrysts in a fine-grained, gray-green ground mass, and is commonly referred to by the field term QFP. Typically, the dacite is only slightly to visually unaltered, with local quartz, iron carbonate, chlorite +/- sericite alteration occurring locally.

Recent work on the project has continued in the form of providing requested information and figures for the production of the Acid Generating Rock Mitigation Plan developed for MnDOT and the Highway 169 Technical Working Group. Barr Engineering has been selected to perform the on-site implementation of the plan, and NRRI personnel have been assisting the Barr personnel by providing details about our work as needed.

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Appendix A: Field Data

Field Data Sheet.xlsx
(Excel spreadsheet included separately with this report)

Appendix B: NRRI Field Drill Hole Logs

(PDF files included separately with this report)

Appendix C: MnDOT Drill Hole Log Scans

(PDF files included separately with this report)

Appendix D: Field Photos

(JPG files included separately with this report)

Appendix E: NRRI Drill Hole Log Scans

(PDF files included separately with this report)

Appendix F: Summary Drill Hole Log Spreadsheet

Summary Drill Hole Log Sheet.xlsx
(Excel spreadsheet included separately with this report)

Appendix G: Drill Core Photos Coleraine

(JPG files included separately with this report. The photo naming scheme is based on drill hole number and box footage. For example, BH-001_0_10 would translate to drill hole BH1, the interval from 0-10 feet.)

Appendix H: Cross-Sections

(PDF files included separately with this report)

Appendix I: Stratigraphic Columns

(PDF files included separately with this report)

Appendix J: ALS Minerals Geochemistry

(PDF files included separately with this report)

Acid Base Accounting testing limits

Analysis	Units	Detection limit
NP	tCaCO3/1Kt	1
pH	Unity	0.1
NNP	tCaCO3/1Kt	1
MPA	tCaCO3/1Kt	0.3
Ratio (NP:MPA)	Unity	0.01
S	%	0.01
FIZZ RATING	Unity	1

ME-MS41, Ultra-Trace Level Methods Using ICP- MS and ICP- AES limits

Element	Symbol	Units	Lower Limit	Upper Limit
Aluminum	Al	%	0.01	25
Antimony	Sb	ppm	0.05	10000
Arsenic	As	ppm	0.1	10000
Barium	Ba	ppm	10	10000
Beryllium	Be	ppm	0.05	1000
Bismuth	Bi	ppm	0.01	10000
Boron	B	ppm	10	10000
Cadmium	Cd	ppm	0.01	1000
Calcium	Ca	%	0.01	25
Cerium	Ce	ppm	0.02	500
Cesium	Cs	ppm	0.05	500
Chromium	Cr	ppm	1	10000
Cobalt	Co	ppm	0.1	10000
Copper	Cu	ppm	0.2	10000
Gallium	Ga	ppm	0.05	10000
Germanium	Ge	ppm	0.05	500
Gold	Au	ppm	0.2	25
Hafnium	Hf	ppm	0.02	500
Indium	In	ppm	0.005	500
Iron	Fe	%	0.01	50
Lanthanum	La	ppm	0.2	10000
Lead	Pb	ppm	0.2	10000
Lithium	Li	ppm	0.1	10000
Magnesium	Mg	%	0.01	25
Manganese	Mn	ppm	5	50000
Mercury	Hg	ppm	0.01	10000
Molybdenum	Mo	ppm	0.05	10000
Nickel	Ni	ppm	0.2	10000

Element	Symbol	Units	Lower Limit	Upper Limit
Niobium	Nb	ppm	0.05	500
Phosphorus	P	ppm	10	10000
Potassium	K	%	0.01	10
Rhenium	Re	ppm	0.001	50
Rubidium	Rb	ppm	0.1	10000
Scandium	Sc	ppm	0.1	10000
Selenium	Se	ppm	0.2	1
Silver	Ag	ppm	0.01	100
Sodium	Na	%	0.01	10
Strontium	Sr	ppm	0.2	10000
Sulphur	S	%	0.01	10
Tantalum	Ta	ppm	0.01	500
Tellurium	Te	ppm	0.01	500
Thallium	Tl	ppm	0.02	10000
Thorium	Th	ppm	0.2	10000
Tin	Sn	ppm	0.2	500
Titanium	Ti	%	0.005	10
Tungsten	W	ppm	0.05	10000
Uranium	U	ppm	0.05	10000
Vanadium	V	ppm	1	10000
Yttrium	Y	ppm	0.05	500
Zinc	Zn	ppm	2	10000
Zirconium	Zr	ppm	0.5	500

Appendix K: Summary Geochemistry Spreadsheet

Master_Acid_Base_ALS_Hwy_169_Rock_type_20160921.xlsx
(Excel spreadsheet included separately with this report)

Appendix L: Plate 1 – Geologic Map of the Eagles Nest Project

(PDF file included separately with this report)