

Appendix 17

Work Plans

- Appendix 17.1** **2016/2017 Geotechnical Investigation Work Plan**
- Appendix 17.2** **Monitoring Wells North of the Mine Site: Installation and Hydrogeologic Monitoring Plan**
- Appendix 17.3** **NorthMet Pit: Conceptual Plan for Bedrock Groundwater Flow Mitigation**
- Appendix 17.4** **Engineered Wetlands Pilot Scale Testing Work Plan**

Appendix 17.1

2016/2017 Geotechnical Investigation Work Plan

2016/2017 Geotechnical Investigation Work Plan - This document is no longer included in the Application. It was previously submitted as part of version 1 of this Application; this document has since been removed from the Application, and the work began at the Plant Site. Agency review (DNR and MPCA) of this work plan was on a separate timeline than this Application.

Appendix 17.2

Monitoring Wells North of the Mine Site: Installation and Hydrogeologic Monitoring Plan

This document is no longer included in the Application. Due to the timing of this work, it is going through agency review (DNR and MPCA) on a separate timeline than this Application.

Appendix 17.3

NorthMet Pit: Conceptual Plan for Bedrock Groundwater Flow Mitigation

Plan



NorthMet Pit: Conceptual Plan for Bedrock Groundwater Flow Mitigation

Project I.D.: 17P777

**Poly Met Mining, Inc.
St. Paul, Minnesota**

December 2017



NorthMet Pit: Conceptual Plan for Bedrock Groundwater Flow Mitigation

Project ID: 17P777

Prepared for
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Prepared by
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December 2017

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NorthMet Pit: Conceptual Plan for Bedrock Groundwater Flow Mitigation

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List of Abbreviations, Acronyms, and Symbols

%	percent
cm/s	centimeters per second
EIS	Environmental Impact Statement
gpm	gallons per minute
MDNR	Minnesota Department of Natural Resources
PolyMet	Poly Met Mining, Inc.
Project	NorthMet Project
RQD	Rock Quality Designations

1 Problem Statement

The Poly Met Mining, Inc. (PolyMet) NorthMet Project (Project) will involve construction of an open pit mine approximately 3 miles long, 0.5 miles wide and 700 feet deep. The pits will be excavated through up to 60 feet of unconsolidated, variably saturated glacial till underlain by variably-fractured rocks including the igneous Duluth Complex and the sedimentary/metamorphic Virginia Formation. A plan view and cross section of the proposed open pits are shown on Figures 1 and 2.

Both the Virginia Formation and the Duluth Complex rocks that will be intersected during pit excavation are generally highly indurated and competent, exhibiting Rock Quality Designations (RQD) in excess of 95 percent (%) in most intervals (Golder, 2006). Fractures are present throughout the full extent of the proposed pit depth. Some drill holes have shown slightly greater fracture prevalence in the uppermost several meters of both the Virginia Formation and the Duluth Complex. Fracture frequencies are typically less than one per foot, with broken intervals that may correspond to fault locations showing frequencies of 20 fractures per foot or greater (Golder, 2006).

Analysis of the groundwater hydrology of the Mine Site was performed as part of the Environmental Impact Statement (EIS) (MDNR et al., 2015). This analysis included a quantitative characterization of bedrock hydrogeology and included pumping tests, water-level measurements, and numerical modeling of groundwater flow under both current conditions and proposed conditions in which the pits are excavated and operating as a groundwater sink. Using field-measured hydraulic conductivity values and water levels to calibrate the model, subsequent simulations indicated moderate groundwater inflow to the pits from surrounding bedrock (MDNR et al., 2015). Given the minimally fractured nature of the majority of bedrock at the Mine Site modest pit inflow rates are the generally expected condition. High rates of pit inflow from bedrock, if they occur, are expected to be limited to localized areas where open fractures or broken/fault zones intersect pit walls. Due to the sparse and discontinuous nature of open fractures and broken or fault zones, predicting if and where these features might intersect pit walls is not possible over the majority of the pit shell.

To estimate the impact of pit inflow on surrounding surface water resources, particularly wetlands, an evaluation of groundwater data from existing open pit operations on the Mesabi Iron Range was performed (MDNR et al., 2015). As documented in the EIS (MDNR et al., 2015), six factors including changes in wetland hydrology due to pit dewatering were considered in assessing potential indirect effects to wetlands. To assess potential changes in wetland hydrology due to pit dewatering, two analog models were used. The results of this analysis is provided in the EIS (MDNR et al., 2015) and were factored into the *Monitoring Plan for Potential Indirect Wetland Impacts* (Barr, 2017).

The model of groundwater flow documented in the EIS (MDNR et al., 2015) was also used to evaluate water flow between the pits and the groundwater system following cessation of operations when the pits will refill via groundwater inflow and precipitation capture. This analysis indicated groundwater will flow into the pits along the northern perimeter of the pits and pit water will flow into the groundwater system along the southern perimeter of the pits.

Outflow from the pits along its southern perimeter may contribute to constituent migration in groundwater following closure.

Based on the preceding summary of pit and bedrock groundwater analysis performed in support of the EIS, the following potential Project impacts are identified:

1. Groundwater inflow from bedrock could be several hundred gpm or higher. Costs will be imposed on the Project to pump, remove, and treat pit water that are directly proportional to the rate of pit inflow.
2. Additional costs may be imposed on the Project to control pit inflow water to protect haul roads and other pit infrastructure, to maintain work areas, and to ensure slope stability.
3. Locally high discharge from productive fractures or fault zones could damage or potentially damage haul roads and pit slopes.
4. Rates of pit groundwater inflow have been estimated for each year of planned operations. Indirect impacts to wetlands near the pits may occur as a result of groundwater inflow to the pits. Mitigation, including measures that might include reconstruction or wetlands banking, will be required and undertaken should such impacts materialize. Pit inflow rates that substantially exceed initial estimates could heighten the potential for indirect wetlands impacts resulting from pit inflow and groundwater drawdown.
5. If open faults or fractured/broken zones create conditions of abundant pit inflow, such features would also contribute to increased outflow from the pits to the bedrock groundwater system during and after refilling of the pits. Larger outflow rates would translate to larger constituent migration rates from pit water into groundwater.

Items 3, 4, and 5 in the preceding list represent pit inflow/outflow impacts that might exceed those developed in the analysis upon which Project permits are based and could require corrective action or mitigation, should such impacts occur. An attractive mitigation strategy for controlling bedrock groundwater flow to and from the pits is the use of injection grouting to partially seal or close productive fractures, faults, and/or broken zones. Grout curtains are widely used for groundwater control in both unconsolidated deposits and fractured and porous rock. Grout curtains differ from grout or slurry walls in that the latter consists of an excavated trench filled with low-permeability grout, often mixed with native soil or earthen material. Alternatively, a grout curtain is constructed by drilling a series of purposely spaced and oriented bedrock drill holes and injecting grout designed for site-specific conditions into surrounding rock to fill pore spaces, fractures, and broken or fault zones.

Construction of a grout curtain enclosing the entire pit shell as a preventative measure is not expected to be warranted, given the minimally-fractured nature of the majority of rock surrounding the proposed pits. Accordingly, use of grout curtain(s) at the Mine Site as a mitigation measure will be considered as a mitigation measure in localized reaches and at specific, targeted depths to mitigate problematic pit inflow resulting from localized fractures, fractured zones, and/or fault zones if problematic pit inflow is observed. Problematic pit inflow is defined as that which gives rise or may give rise to impacts identified in items 3 or 4 above.

Prior to implementing grout curtain mitigation measures, a formal work plan would be developed and provided to MDNR for review. Grout curtain mitigation measures described within this document are provided as a summary of the measures that could be undertaken and their potential benefits in the event that problematic pit inflow is observed during operations.

2 Determination of When and Where Pit Inflow Mitigation is Required

Construction of grout curtains to control groundwater flow is a mature technology and is common in projects such as excavation dewatering, embankment seepage control, dam underflow mitigation, and dam foundation stabilization. In many such projects, grout curtains are constructed prior to the commencement of excavation, dewatering, or structure construction. Such practice simplifies the construction of a grout curtain because hydraulic gradients remain at natural or ambient levels. Ambient or small hydraulic gradients translate to small groundwater flow rates which simplify grout injection and cause less washout of grout during the injection process. Large hydraulic gradients occurring after or during construction require thicker grouts to prevent washout. Thicker grouts possess higher viscosity which reduces the mobility of grouts and the extent of coverage associated with any one grout hole.

Grout curtains have also been installed as remediation or mitigation measures to control groundwater flow after construction has accentuated hydraulic gradients and groundwater flow rates. Examples of such practice include grout curtains constructed in dam foundations and impoundment embankments experiencing stability problems due to excessive groundwater flow or seepage rates.

As noted previously, construction of a grout curtain prior to pit excavation is impractical because the length and depth required to completely encircle the pits would entail prohibitive cost. Additionally, construction of localized curtain segments prior to pit excavation is not practical because identifying the portions of the pit perimeter where pit inflow mitigation might be required is precluded by the inability to predict the location of such zones due to the lack of continuity exhibited by open fractures and fault zones.

Accordingly, bedrock groundwater flow mitigation would be considered during pit excavation and refilling if any of the following conditions are observed:

- ◆ Pit inflow occurs from localized features such as fractures, fracture zones, or faults, at sufficient rate to present a hazard such as pit slope instability or a management challenge relative to pit infrastructure such as haul road maintenance.
- ◆ Pit inflow rates substantively exceed expected inflow rates developed during project permitting.
- ◆ Adverse, indirect wetland impacts are observed as part of the monitoring described in the Monitoring Plan for Potential Indirect Wetland Impact (Attachment F, PTM Application Appendix 18.2) that could be reasonably attributed to mine pit dewatering. The regulatory criteria that indicate an adverse, indirect wetland impact are provided in Section 16 of PTM Application Appendix 18.2. If wetland impacts are observed and such impacts are not eliminated via actions described in this plan, wetland mitigation would be required and undertaken.

- ◆ Bedrock groundwater quality (during or after pit flooding) downgradient of the pits displays persistent constituent concentrations that materially exceed projected concentrations and water quality standards established in project permit documents.

3 Field Investigation to Define Problem Extent and Design Mitigation

If or when one of the prior “mitigation triggers” is observed, the first response would be to review the problem and evaluate whether or not mitigation of pit groundwater inflow/outflow is warranted and feasible. The key element that would determine whether consideration of grouting is warranted is the presence of problematic flow that occurs, at least in part, in localized areas and from identifiable or discrete features or zones. As noted previously, grout curtain mitigation of pit inflow is not envisioned for controlling diffuse pit inflow that is distributed over expansive portions of the pit shell.

When a review of a potential pit groundwater inflow/outflow problem determines that grout curtain mitigation merits consideration, the following sequence of evaluations and analysis would be initiated:

1. Identify, analyze, and survey the zone(s) and feature(s) present in the pit wall that are contributing to excessive inflow. This step would include a careful geologic inspection of the features displayed in the pit wall.
2. Review existing geologic data (inferred fault maps, drill hole logs, loss of circulation occurrences during exploratory and geotechnical drilling, geophysical logs, core photographs, and archived core), in conjunction with the results from step 1, to define the orientation, location, and extent of structures contributing to the problematic inflow.
3. Using the results of steps 1 and 2, determine if conditions appear favorable to grout curtain mitigation of pit inflow/outflow. If conditions are favorable, proceed with the design of a drilling program to refine the location and orientation of the structures and gather structure data (extent, permeability, and aperture) required for design of a grout curtain. If conditions identified by this drilling program appear unfavorable for grout curtain mitigation of pit inflow, evaluate alternative management strategies.

The occurrence of problematic inflow does not mandate the commencement of drilling and grouting; rather, the occurrence of problematic pit inflow would result in an evaluation of the merits of a grouting program or other possible management responses. If, during the course of this preliminary evaluation, an alternative mitigation measure is identified or circumstances are identified that indicate grouting would be ineffective or unnecessary, further pursuit of grout curtain mitigation for the particular location would be suspended and alternative management strategies would be considered.

Step 1 following the identification of a pit groundwater management problem would involve geologic inspection and surveying of fractures and faults by a professional geologist and surveyor to determine a preliminary estimate of the feature orientation and to locate them in three-dimensional space for plotting and analysis relative to existing geologic data.

Step 2 would entail the spatial analysis and plotting of structure data for fractures and faults that can be identified in lithologic logs, circulation logs, core, geophysical logs and core photographs

from existing drill holes located adjacent to the pit shell in the vicinity of the features contributing to excessive pit inflow. Steps 1 and 2 would combine to provide an improved projection of the location, orientation, and continuity/extent of the producing fractures/faults. Determining orientation would be a primary goal of steps 1 and 2 because orientation would be the primary determinant in designing investigation drilling that successfully intersects the producing features.

Once the expected location and orientation of producing features have been projected from the pit shell into the adjacent unexcavated rock mass, a series of investigative, angled drill holes would be advanced to intersect the producing fractures and/or fault(s). This work constitutes step 3 of the field investigation. Step 3 entails a limited drilling and field testing program designed to confirm the distribution of producing features beyond the pit shell and quantify their hydraulic properties (aperture and hydraulic conductivity). A summary of existing bedrock hydrogeologic characteristics that would influence pre-grout field investigations and the design of individual grouting programs is provided in Table 1.

Sufficient drill holes would be installed to locate producing features with a high degree of certainty. Drill holes would be angled such that intersection angles with primary producing features are as large as practicable. Drilling would be performed using a rotary down-hole percussion water hammer drilling method (Wassara system or equivalent) to avoid air-entrained cuttings fouling of open features that would subsequently impede grouting efficiency. Field data collection would include optical televiewer logging, caliper logging, and packer testing. Televiewer logging would be used selectively for confirming interception of the producing features, confirming feature orientation, and defining feature aperture which influences the design of grout mixes used for injection and sealing. Field investigation drill holes would be planned to allow integration into the final grout hole layout whenever possible and would be grouted to prevent cross-circulation routes and to enhance the overall grouting program effectiveness.

Packer testing, involving dual- or single-packer testing to allow isolation of discrete features or feature intervals would be performed in each hole to aid in locating target (producing) zones and to calculate permeability. Packer testing would conform to ASTM D4630 and ASTM D4631. The goal of packer testing is to determine interval-specific hydraulic conductivity or permeability to aid in the design of the grout mix, to identify target zones to be grouted, and to estimate projected grout volumes per target zone. Because the typical lower limit of hydraulic conductivity achieved via grouting is 1×10^{-6} centimeters per second (cm/s) and Duluth Complex and Virginia Formation rocks exhibit a range of bulk hydraulic conductivities already encompassing this magnitude, grouting would only be effective in reducing the permeability of zones exhibiting a relatively high frequency of open fractures or the presence of open or broken fault zones. Packer testing would serve to confirm grouting target zones initially identified via three-dimensional mapping of pit wall survey data, lithologic and drilling logs, and televiewer and caliper logs.

Table 1**Bedrock Characteristics and Properties, NorthMet Mine Site**

Rock Property	NorthMet Values/Properties
Duluth Complex Rock Type	Precambrian Igneous intrusive mafic rocks; largely troctolite and gabbro
Virginia Complex Rock Type	Precambrian sedimentary and contact metamorphic rocks consisting of argillite, siltstone and greywacke
Strike and Dip of Duluth Complex Intrusion	Strike is approximately N56°E Dip is 15 – 25° to SE
Median Rock Quality Designation-Duluth Complex	Unit 1 = 99.2% Unit 2 = 97.5% Unit 3 = 99.2% Unit 4 = 99.6% Unit 5 = 99.2% Unit 6 = 99.2% Unit 7 = 99.2%
Median Rock Quality Designation-Virginia Formation	90.8%
Primary Rock Porosity	Assumed less than 5% inferred from origin, mineral composition and core inspection.
Faults	Inferred faults predominant strike ENE, NE, and NNE; minor faults strike NW. Drill hole logs show sporadic, discontinuous evidence of faults and broken zones ranging from moderately broken and open to shattered and very open. Broken/open fault zones do not show continuity between drill holes nor alignment with inferred fault mapping.
Median Fracture Frequency-Duluth Complex	Unit 1 = 0.4 fractures/ft Unit 2 = 0.7 fractures/ft Unit 3 = 0.5 fractures/ft Unit 4 = 0.5 fractures/ft Unit 5 = 0.6 fractures/ft Unit 6 = 0.5 fractures/ft Unit 7 = 0.5 fractures/ft
Median Fracture Frequency-Virginia Formation	1.2 fractures/ft
Hydraulic Conductivity-Duluth Complex	10^{-7} - 10^{-5} cm/s
Hydraulic Conductivity-Virginia Formation	10^{-7} – 10^{-4} cm/s

Sources: Golder, 2006; MDNR et al., 2015.

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Checked by: MJV2

4 Mitigation Design, Construction, Verification

4.1 Grout Hole Layout Design

Once the target zone or feature(s) have been reasonably identified in terms of position, orientation, extent, frequency, and aperture, a grout injection hole network would be designed. The grout hole network is typically designed as a sequence of “split-distance” holes as shown on Figure 3. The first or primary sequence of split-distance holes are spaced relatively far apart (up to 40 feet). Subsequent sequences are commonly termed “secondary holes,” “tertiary holes,” “quaternary holes,” and “verification holes.” Most grout curtains involve primary and secondary sequences at a minimum. All grout curtain programs require a verification sequence of holes to provide a quality assurance check on the coverage and permeability reduction of the main sequences. Figure 3 illustrates a program involving three main split distance sequences followed by a verification sequence. Drill holes would be advanced via rotary percussion water hammer (Wassara system or equivalent). Use of air-rotary drilling is prone to fouling of open features with air-entrained cuttings. Cuttings entrapped in features targeted for grouting reduce the mobility and effectiveness of grouting but do not contribute to meaningful reductions in permeability or seepage. Drill hole diameter is typically 95 millimeters. Two and sometimes more parallel rows of grout holes, commonly at offset vertical angles, are often used to add thickness to the grout curtain perpendicular to the flow direction, thereby providing more effective permeability reduction and a factor of safety relative to grout washout prevention. Each completed drill hole would be down-hole surveyed using a system such as Boretrack or equivalent to verify proper hole orientation and intersection with the target zone.

Spacing for the primary sequence of grout holes may be as large as 40 feet. Spacing is a function of the permeability of the rock or feature being grouted and the viscosity of the grout to be injected. As noted previously, the host rock at the Mine Site is of extremely low permeability and would be effectively impervious to any grout mix. As such, the permeability of conductive fractures or broken/open fault zones would be the controlling feature relative to hole spacing. Also affecting hole spacing would be the hydraulic gradients across the target zone. Greater hydraulic gradients require low-viscosity grouts to reduce washout potential. Low-viscosity grouts require smaller hole spacings to promote complete grout infiltration throughout the target features or zones. If large problematic producing zones are encountered in the pit wall, thereby requiring large grout curtains for mitigation, application of numerical modeling of the grout inject process may be applied to optimize the spacing of grout holes, injection pressures, and grout viscosities, such that the number of grout holes and the volume of grout required is minimized.

4.2 Grout Mix Design

Grout mix design is commonly based on an empirical approach using rock or feature permeability, hydraulic gradients, and hole spacing as variables. As noted previously, numerical simulation of different grout mixes may be used in cases where extensive grout curtain lengths are required and control of costs requires optimization of grouting efficiency. Grout mix components commonly include cement, water, and bentonite. Superplasticisers may be added if the target features are relatively small aperture fractures requiring low-viscosity grout for adequate penetration. Conversely, high hydraulic gradients and/or large aperture fractures require high-viscosity grouts to prevent washout. Increased viscosity can be obtained by adding

sand or thickening additives such as Rheomac UW-450 cellulose thickener, which is also effective in preventing bleeding of cement content and dilution by formation water.

Suitable grout mix design may be tested and verified by initial injection of multiple grout mixes in distinct grout holes combined with comparison of injection monitoring data and televiewer logging adjacent holes to verify radial migration of grout throughout the target zone.

4.3 Grout Injection

Once the grout mix design has been finalized and verified via preliminary field testing, grout injection proceeds first in all primary holes followed by injection in secondary and then tertiary holes. Grout injection in verification holes is performed after all quality assurance testing and data collection have been completed in the verification holes.

During injection, several parameters are computer monitored to allow the grouting engineer to ensure successful and safe grout delivery to the target features or zone. A computerized software program such as *CAGES* (ECO Grouting Specialists, 1997) or equivalent would be used to ensure rapid data acquisition and interpretation which aids in the management and optimization of the grout injection process. Table 2 summarizes the parameters that would be monitored during injection together with the information provided by each parameter.

Table 2
Grout Parameters Monitored During Injection for Optimization of Grouting Effectiveness

Grout Injection Parameter	Information Provided
Grouting Pressure (range from zero to in excess of 90 bar)	Successful grouting should display steady pressure until grout refusal (setting) occurs as indicated by pressure increase. Steady pressure beyond target refusal time signals runaway grout. Rapid pressure fluctuations indicate potential plastic fracturing.
Grout Flow Rate (gpm)	Grout flow rate should be steady and then decline at target refusal or slowly decline toward zero at refusal. Steady flow rate beyond target refusal time indicates cavity encountered or runaway grout. Spike in flow rate indicates plastic fracturing. Slow increase in flow rate indicates ground heaving.
Grout Volume Injected (Take) (gallons)	Compare with target volume. Overshooting target volume indicates runaway grout, cavity or heaving.
Apparent Grout Lugeon (Lu)	Should decline toward zero for successful grouting. Spikes indicate plastic fracturing. Steady value indicates runaway grout or cavity.
Theoretical Grout Spread (feet)	Reveals if delivery to targeted grout zone is achieved.

Prepared by: DRD
Checked by: MJV2

Each hole would be grouted in stages from the bottom up. Stages are typically 10 feet long. During injection, in addition to monitoring the parameters in Table 2, pH and flow rate at the pit wall would be monitored and observed, respectively. Elevated pH would indicate the grout is intersecting the required target zone, as would observation of declining flow discharging at the pit wall. Failure to observe increasing pH or decreasing flow would necessitate re-evaluation of the projected target zone beyond the pit wall and the location and orientation of the grout holes.

4.4 Quality Control, Assurance, and Testing

Monitoring of the data summarized in Table 2 is one element of the construction-phase quality control. Additional quality control testing performed during grouting includes Marsh-cone testing, bleed testing, and temperature monitoring of grout mix. All three tests are performed a minimum of once per batch per grouting phase/interval. Test results outside the acceptable range specified in the mix design require termination of injection and immediate water washout of that interval of the hole that received out-of-specification grout.

Completion of grout injection in all planned holes (primary, secondary, tertiary, etc.) and lines is then be followed by drilling a series of verification holes. Verification holes would be located and drilled to intersect the same zone or features targeted by the main grouting program but would be located and spaced between the main set of grout holes. If a multi-line, grout-hole program is used, some or all of the verification holes would be located between the main grout-hole lines. Unlike the main grout holes, verification holes would be drilled with a core rig to allow core inspection and photography to provide visual confirmation of grout delivery and sealing throughout the entire target zone. Televiewer logging may also be performed to visually confirm grout propagation throughout the target zone. Additionally the grouting pressure curve, flow rate, and volume delivered would be recorded and compared for each verification hole to the final sequence of split-spacing holes. The objective is to find higher injection pressures and lower flow rates early in the time series recorded for each verification hole and to observe lower overall grout volumes injected relative to the last split-spacing sequence of holes. Higher pressures, lower flow rates, and lower injected volumes all indicate a relative lack of space available for grout invasion, meaning that the prior sequences of grout injection of successfully filled and sealed open fractures, faults, and broken zones.

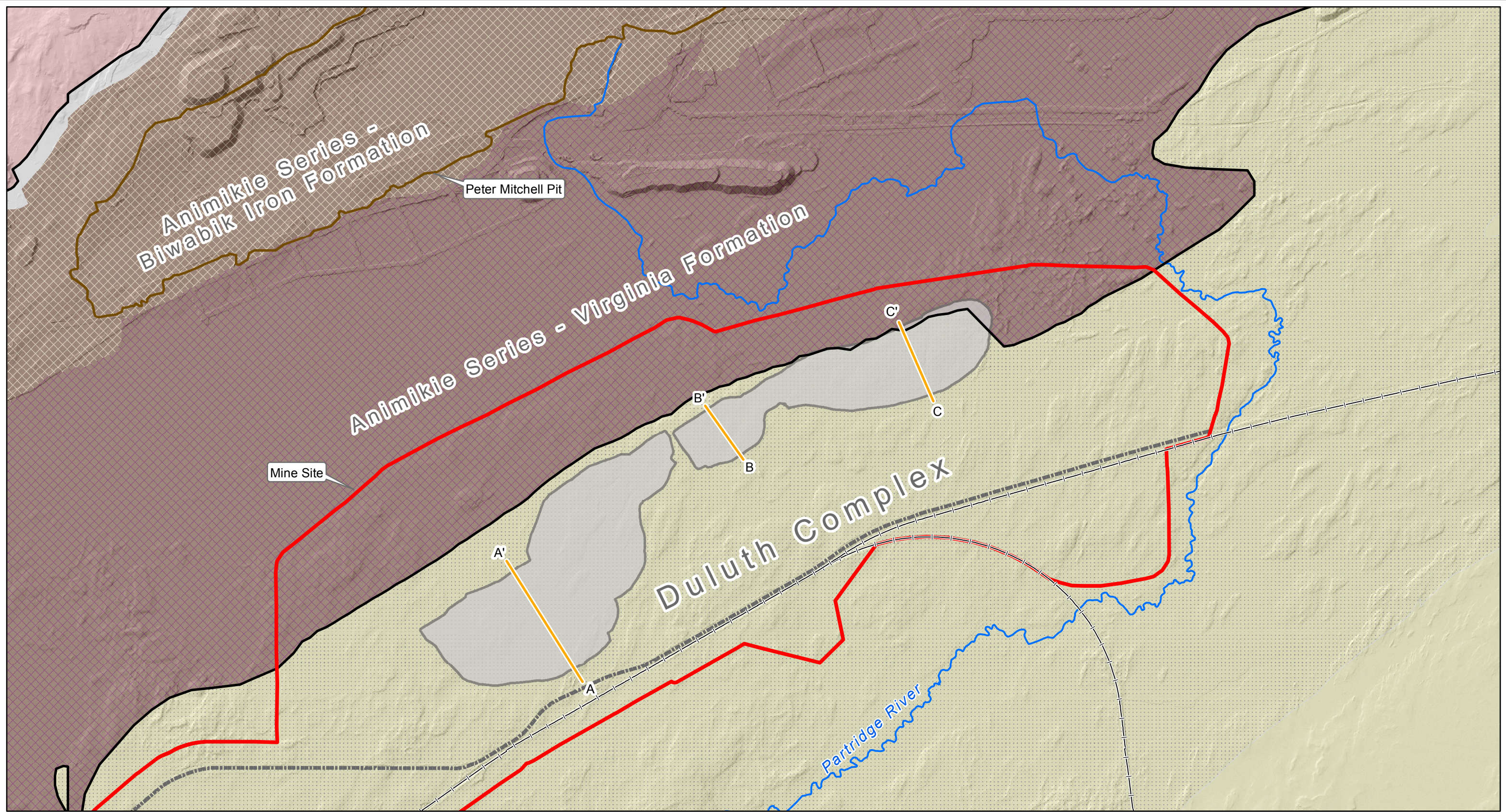
Additionally, prior to injection of grout in verification holes, packer testing would be conducted to determine residual, post-grouting permeability. Comparison of verification hole packer test hydraulic conductivities with those measured in the main grout holes prior to grouting would provide the final indication that the intended reductions in hydraulic conductivity were achieved throughout the zone. An example of this comparison is presented on Figure 4. A successful grouting program would exhibit a steady decline in permeability within the target zone as primary, secondary, and tertiary holes are successively grouted. Verification holes should show permeabilities lower than all other holes. Failure to achieve this result indicates potential ungrouted or partially grouted zones within the target area. Because the verification holes are themselves grouted, it is possible that an ungrouted zone is remedied by the grouting of the verification hole that identified the ungrouted zone. Additional verification holes are called for in such instances.

Lastly, successful grouting would ultimately be validated by substantial reduction in the flow observed at the pit wall. In instances where the pit inflow problem involved excessive indirect impacts to wetlands, successful grouting would ultimately be demonstrated by a reversal or reduction in the dewatering impacts observed in wetlands surrounding the pits and will be monitored through the *Monitoring Plan for Potential Indirect Wetland Impacts* (Barr, 2017).

5 References

- ASTM D4630. *Standard Test Method for Determining Transmissivity and Storage Coefficient of Low-Permeability Rocks by In Situ Measurements Using the Constant Head Injection Test*. 2008.
- ASTM D4631. *Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In Situ Measurements Using Pressure Pulse Technique*. 2008.
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- Golder Associates, 2006. *Recommendation for NorthMet Open Pit Rock Slope Designs, NorthMet Mine Project*. Submitted to PolyMet Mining Corporation, 2350-1177 West Hastings Street, Vancouver, BC. June 2006.
- Minnesota Department of Natural Resources, United States Army Corp of Engineers, and United States Forest Service, 2015. *Environmental Impact Statement, NorthMet Mining Project and Land Exchange*. November 2015.

Figures



Notes

1. Project Features supplied by Barr Engineering.
2. Geology Sources: Jirsa, M.A., Chandler, V.W., and Lively, R.S., 2005, Bedrock Geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey Miscellaneous Map M-163, scale 1:100,000. Severson, M.J., and Miller, J.D. Jr., 1999, Bedrock Geology of the Allen Quadrangle: Minnesota Geological Survey Miscellaneous Map 91, scale 1:24,000.

Legend

- Dunka Road
- Existing Private Railroad
- Rivers and Streams
- Cross Section Locations Mine Site
- Mine Pits (Year 20)
- Proposed Project Area Boundary

Bedrock Geology (Severson and Miller, 1999)

- Animikie Series
- Duluth Complex
- Duluth Complex - Partridge River Intrusion
- Giants Range Crystalline Rocks
- Animikie Series - Virginia Formation
- Animikie Series - Biwabik Iron Formation



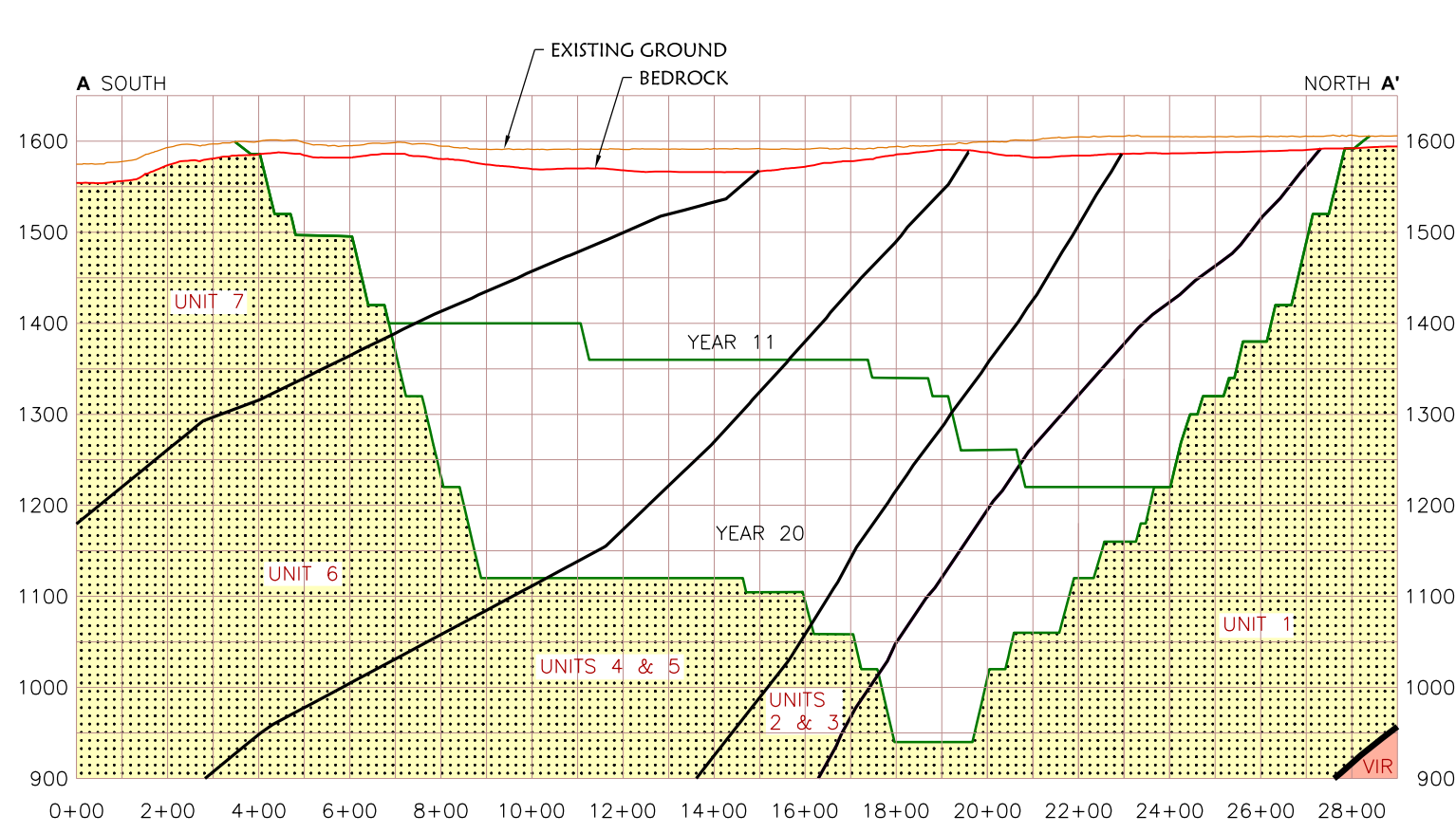
Foth Infrastructure & Environment, LLC			
REVISED	DATE	BY	DESCRIPTION
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APPROVED BY: DRD		DATE: JAN. '15	
APPROVED BY:		DATE:	

POLYMET MINING

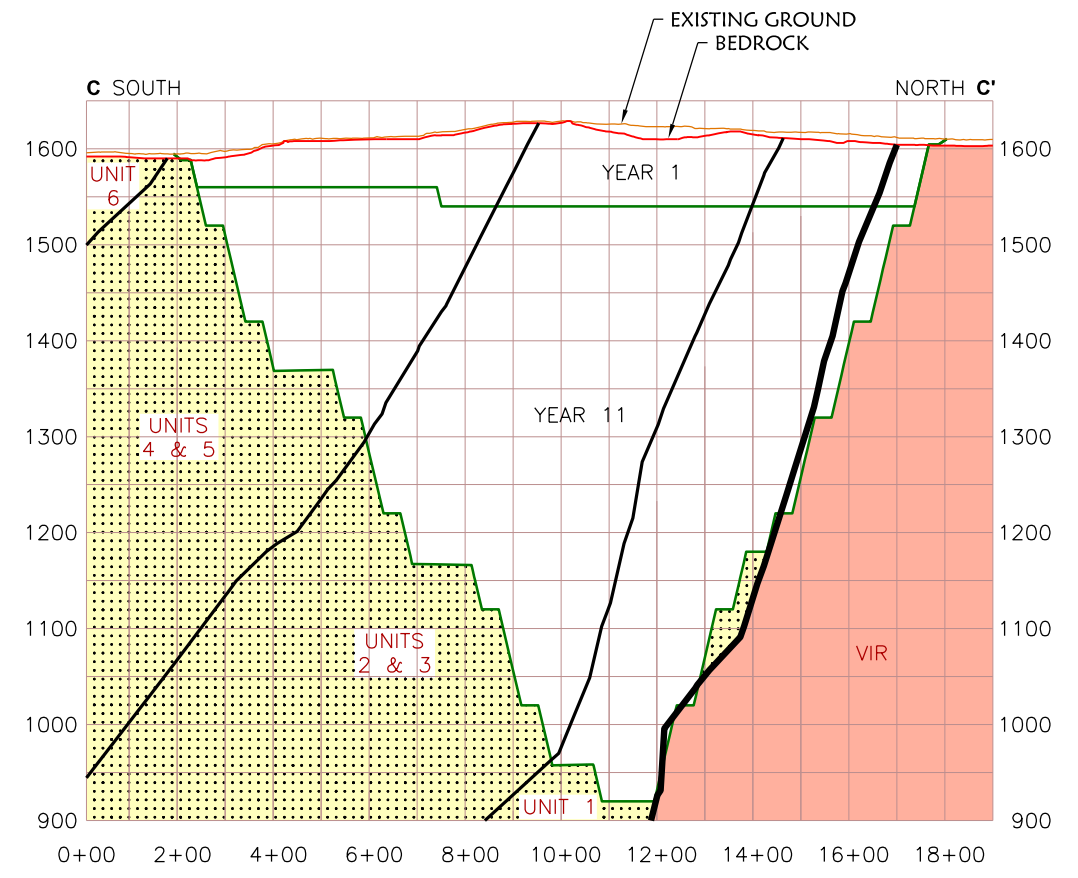
FIGURE 1
 PLAN VIEW OF MINE SITE WITH OPEN PIT FOOTPRINT AND BEDROCK GEOLOGY AS MAPPED AT UPPERMOST BEDROCK SURFACE PERMIT TO MINE APPLICATION HOYT LAKES, MINNESOTA

Scale: 0 1,000 2,000 Feet

Prepared by: DAT Date: JANUARY 2015 Project No: 12P778

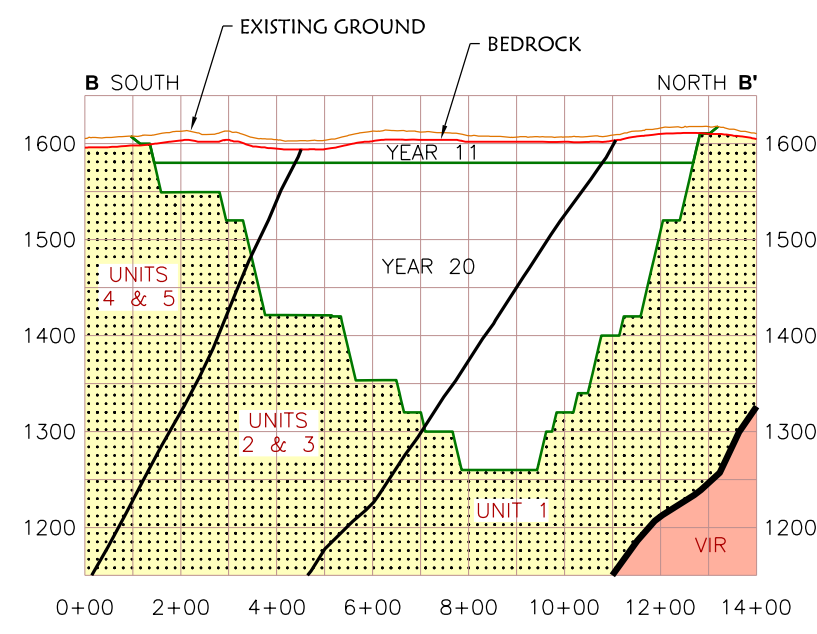


(A) SECTION: WEST PIT
2:1 VERTICAL EXAGGERATION



(C) SECTION: EAST PIT
2:1 VERTICAL EXAGGERATION

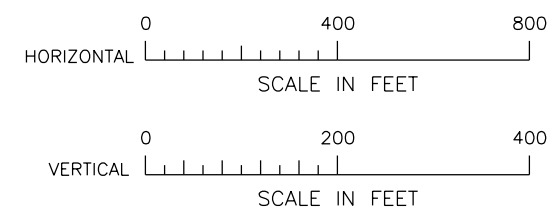
BARR TO PROVIDE OUTLINE OF ORE BODIES ON THESE SECTIONS



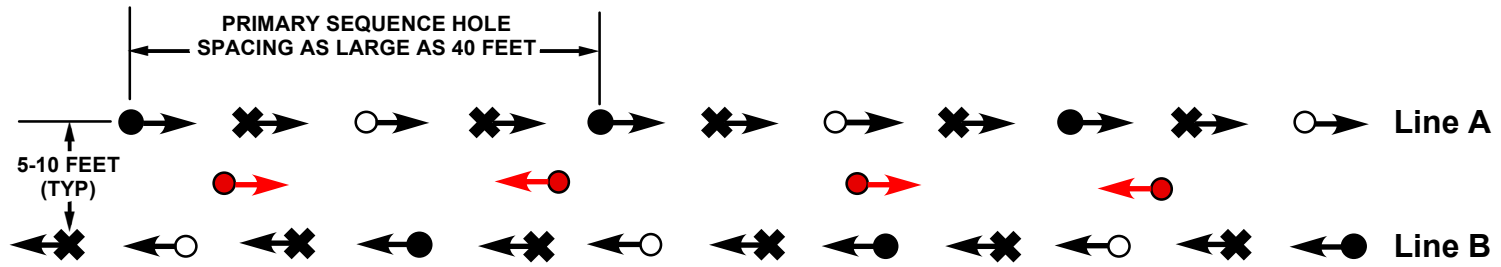
(B) SECTION: CENTRAL PIT
2:1 VERTICAL EXAGGERATION

- LEGEND**
- UNIT 1-7
PARTRIDGE RIVER INTRUSION
DULUTH COMPLEX
 - VIR
VIRGINIA FORMATION
ANIMIKIE SERIES
 - GEOLOGIC CONTACT

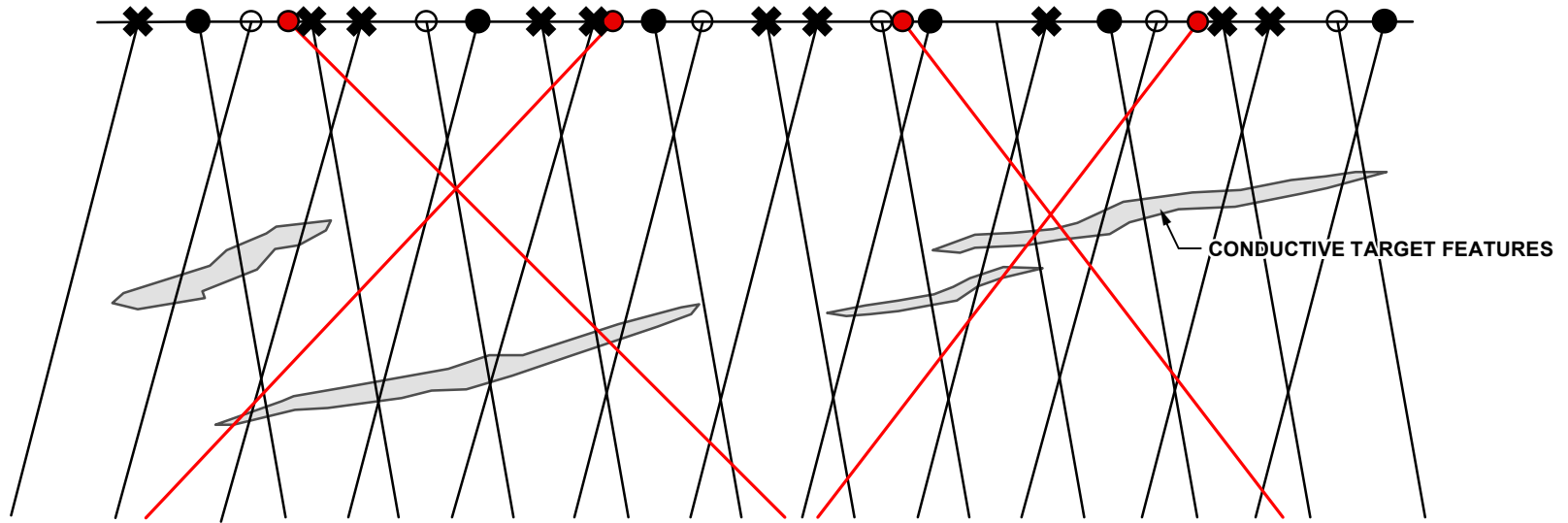
- NOTE:**
1. CROSS SECTION LOCATIONS SHOWN ON FIGURE 3-1.
 2. CROSS SECTION FIGURES PROVIDED BY BARR ENGINEERING COMPANY.
 3. CENTRAL PIT MINING WOULD BE COMPLETED IN MINE YEAR 16.



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REVISED	DATE	BY	DESCRIPTION	FIGURE 2 CROSS SECTIONS THROUGH PROPOSED MINE PIT SHOWING PRIMARY BEDROCK GEOLOGY PERMIT TO MINE APPLICATION HOYT LAKES, MINNESOTA	
PREPARED BY: JSL		DATE: AUG. '16		Scale: NOT TO SCALE	Date: AUGUST 2016
REVIEWED BY: DRD		DATE: MAR. '15		Drafted By: JOW	
APPROVED BY:		DATE:		Project No: 12P778	



PLAN VIEW



SECTION VIEW

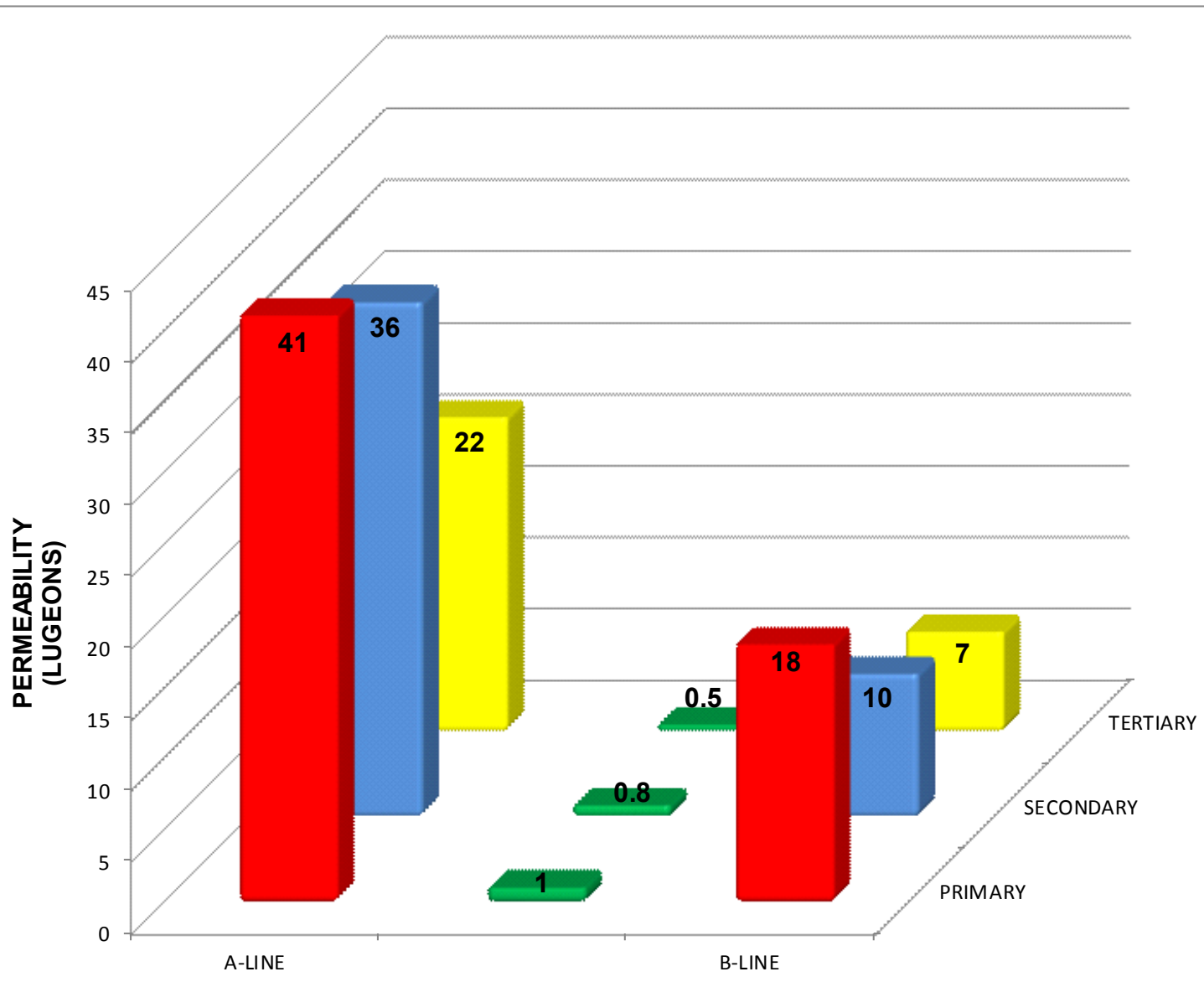
Legend

- Primary Sequence Grout Hole
- Secondary Sequence Grout Hole
- ✕ Tertiary Sequence Grout Hole
- Verification Sequence Hole
- ← Dip Direction of Hole
- ☁ Conductive Target Features



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CHECKED BY: MJV2			DATE: JAN. '15		
APPROVED BY: DRD			DATE: JAN. '15	Scale: NOT TO SCALE	Date: JANUARY 2015
APPROVED BY:			DATE:	Prepared by: BJW1	Project No: 12P778

FIGURE 3
 EXAMPLE OF GROUT HOLE CONFIGURATION
 USING SPLIT SPACING SEQUENCE
 PERMIT TO MINE APPLICATION
 HOYT LAKES, MINNESOTA



Legend

- Primary Sequence Holes
- Secondary Sequence Holes
- Tertiary Sequence Holes
- Verification Sequence Holes



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REVISED	DATE	BY	DESCRIPTION
CHECKED BY: MJV2		DATE: JAN. '15	
APPROVED BY: DRD		DATE: JAN. '15	
APPROVED BY:		DATE:	

POLYMET MINING

FIGURE 4
 HYPOTHETICAL PERMEABILITY COMPARISON
 PLOT FOR MAIN VERSUS VERIFICATION HOLES
 PERMIT TO MINE APPLICATION
 HOYT LAKES, MINNESOTA

Scale: NOT TO SCALE	Date: JANUARY 2015
Prepared by: BJW1	Project No: 12P778

Appendix 17.4

Engineered Wetlands Pilot Scale Testing Work Plan

This document is no longer included in the Application. Due to the timing of this work, it is going through agency review (DNR and MPCA) on a separate timeline than this Application.