**Technical Memorandum: Twin Metals Mining and the Boundary Waters Canoe Area Wilderness, Identifying Flow Pathways**

**Prepared for: Northeastern Minnesotans for Wilderness, Ely MN**

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Twin Metals, Inc, which includes Duluth Metals, Franconia, and Beaver Bay, have acquired interests in federal subsurface mineral rights, including two 1966 leases. Both expired on December 31, 2013, and the leases were not initially renewed. Myers (2013) showed there was a substantial risk that mining these leases could cause leaks or seepage that could reach the Boundary Waters Canoe Area Wilderness (BWCAW). This technical memorandum focuses in more detail on the potential for preferential pathways from the potential mines to allow contaminants to reach BWCAW. This memorandum also considers whether geophysical testing including videos of boreholes or hydrologic tests can be used to prove there is not connection.

The Twin Metals leases lie south of the South Kawishiwi River near and southwest of Birch Lake. The South Kawishiwi River flows west from the BWCA and then joins with the Kawishiwi and flows back into the BWCA. The BWCA is considered an "outstanding resource value water" under the Minnesota statutes (MAR 7050.0180).

The key factor that controls whether transport from a source can reach the BWCAW or points further downstream is the pathway – the route the contaminant flows to the BWCAW. Regardless of the source of the contaminant, once a contaminant reaches surface water, the route to the BWCAW is through streams and rivers (Figure 1). This memorandum considers the pathways through bedrock and surficial aquifers from the source to surface water. It also considers the methods used to estimate or map pathways.

The next section reviews geophysical and hydrologic methods that can be used to determine whether contaminants would reach surface waters. The pathways require both fractures and connectivity among fractures. The next section discusses the literature regarding fractures in the bedrock between possible mines and surface waters. The memorandum concludes with a qualitative risk assessment of transport to the BWCAW from potential leaks in the Birch Lake area. It considers further the evidence that groundwater pathways exist for transport from a leaky mine to surface water that drains to the BWCAW.

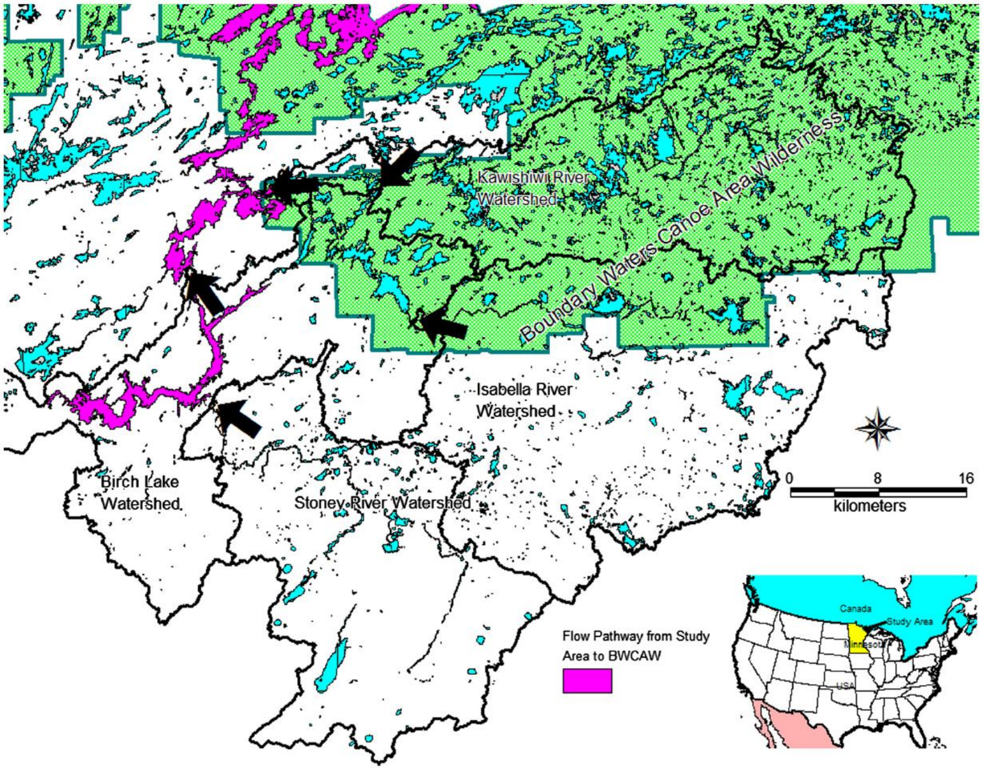


**Fig. 1.** Rainy Headwaters watershed and study area, showing subwatersheds, rivers, and lakes. Arrows are flow direction from watersheds. Watershed boundaries from Dnr100kwatersheds, www.mngeo.state.mn.us/chouse/metalong.html.

*Figure 1: Figure 1 from Myers (2016) showing surface water pathways from the mine leases to the BWCAW.*

## Geophysical Techniques

Geophysical techniques may be used to characterize and monitor a project site developed in fractured rock. Geophysical techniques include a large suite of methods that include downhole measurements that will allow an assessment of the lithology and the fractures. These include several types of gamma measurements, because gamma radiation emanates from the formations at different rates. It may include cameras which can be used to see fractures and where groundwater enters the hole. There are four basic types of investigation that can be used to consider fractures and pathways in bedrock - surface methods, cross-hole methods, borehole methods, and hydrologic tests. Day-Lewis et al (2015) provides the basics for the following summary.

Surface methods include electromagnetic terrain conductivity, which measures specific conductivity over an area. It can be used to map contaminant plumes, conductive features such as ore bodies or buried metal, the depth and thickness of clay layers, and the depth to a fresh/saltwater interface. The only way it can map a fracture zone is if it contains a plume. Another surface method is surface resistivity, which can map depth to bedrock, saturation, porosity, and total dissolved solids. It can be used to identify shallow fracture zones, but is generally limited to shallow fractures delineated by conductive plumes. The method also operates along a transect, so fractures not coincident with the transect are not likely to be intersected.

Surface ground penetrating radar (GPR) can show saturation, lithology, bedrock configuration, and the location of freshwater salt water interface. It can be used in certain situations to identify fractures, although its ability to identify connected fractures is limited (Buursink et al 1999).

Azimuthal surface resistivity can help map lithology and depth to bedrock, saturation, porosity, TDS and possibly identify fracture zones with conductive plumes. The depth of the investigation is limited to 1/3 to 1/5 the array length. The azimuthal self-potential method measures streaming potential, or the electrical potential of current flow. It can provide directions of groundwater flow in fractured rock, bulk anisotropy, and monitor flow in fractures. However, it requires a detailed radial array of non-polarizing electrodes, so the area over which it can map fracture flow is limited. The flow must also be very shallow.

Seismic refraction and reflection measures seismic wave propagation and reflection to provide information about depth to water, bedrock, or subsurface horizons. Both require distinct differences in material to cause reflection from a distinct layer. Time domain electromagnetic resistivity measures resistivity to provide information about lithology, the bedrock surface, and saturation.

A summary of surface methods is that several can map fracture zones, but they are limited to fractures that contain a contaminant plume or conductivity fluid, such as high-TDS water. They are also limited to shallow fractures. They would never be able to map a fracture at depth. In the highly weathered zone near the ground surface near the Twin Metals leases, they could only detect connected fractures if a transect was established over the fracture zone.

Cross-hole methods include electrical resistivity cross-holes methods which measure electrical resistivity between boreholes to identify the location of large, water filled fractures beyond boreholes. If tightly spaced, they can be used to draw a profile of hydraulic connectivity among boreholes within a system. Cross GPR can map radar slowness, the inverse of velocity, which can identify large water-filled fractures and changes in lithology. Cross-hole induced polarization measures impedance between boreholes, which provides an estimate of hydraulic conductivity among pathways. The value of this information would be limited to the profile between boreholes so could indicate a lack of connectivity only with many boreholes. A seismic cross-hole survey measures the travel times for seismic waves between boreholes, which shows seismic velocities, porosity, aquifer stiffness and fractures.

Summarizing, cross-hole methods can provide information about fractures, but only along a profile between two boreholes. A lack of connectivity between two boreholes does not prove there is no connectivity within an area.

Single bore-hole methods, by definition, provide information at a single point, but it is possible to correlate between nearby holes. If a fracture zone is identified at a level that is consistent among holes, it may be assumed to be connected. Tests that identify fractures within a bore hole include caliper tests, gamma tests, and methods that measure electrical resistivity or induced polarization that can identify fracture density which can be correlated among boreholes. An optical televiewer or a video camera can be used to directly view fractures in the wall of the borehole; the view does not extend through the fracture to estimate where it goes.

Hydrologic tests, conducted at a field-scale, that could show connectivity include cross-hole flow tests, tracer studies, and standard pump tests. The first two would show flow between two or more boreholes and standard pump tests would show that pumping pressure in one well could change the hydrostatic pressure, thereby causing drawdown at other wells. Pump tests do not require a direct flow path between wells to show drawdown. Also, a failure to show substantial drawdown does not prove there is no connectivity, but only that the response to stress would require a long time.

Another field scale hydrologic test to estimate fracture flow and directions includes high-resolution temperature measurements, which use temperature gradients to estimate flow. This can be useful to measure flow velocities between boreholes that are known to be connected.

**Flow Pathways between TMW and BWCAW**

A leak on the surface is most likely to flow through the thin surficial aquifer that consists of till or sand and gravel, which is generally less than 3 to 6 m thick. Hydraulic conductivity (K) is extremely variable; Myers (2016) cited sources suggesting K ranges from 0.000003 to 1070 m/d. Flow from surface leaks would not require preferential pathways to reach surface water, but the high K values probably occur in lenses within the till which form high flow pathways.

Underground sources follow a more complicated route to surface water. The underlying bedrock is mostly the Duluth formation, which like most bedrock has low primary permeability and most transport occurs through fractures. Myers summarized the bedrock as:

> The Duluth Complex is a low-permeability intrusive formation with a very low K except possible near some of the infrequent faulting, on which there is little available hydrogeologic data, and in the upper 30 m which is relatively fractured with well yields from 27 to 82 $m^3$/d. The plutonic rocks have primary porosity up to 3%, but the effective permeability is very low because the pores are isolated. The specific capacity of wells in the Duluth Complex ranges from 0.36 to 1.97

> $m^3$/d/m. In bedrock, fractures control permeability and secondary porosity, and also flow paths. (Myers 2016, p 280, references omitted)

The following section considers the potential fractures in the bedrock in the Birch Lake area.

**Fractures in Geologic Formations in the Area**

The Duluth complex hosts the mineralization in the Birch Lake area (Barber et al 2014) and is therefore the primary bedrock formation to consider for fractures that could create pathways. Twin Metals (2013, p 30) describes fractured bedrock in the Birch Lake area as varying from 300 to 350 feet thick, and having an average permeability of 0.054 ft/d. Because most fracture flow occurs over small thicknesses, certainly much less than 300 to 350 feet, it is likely that the permeability is much higher over preferred pathways which could provide the pathways needed for contaminant transport from underground sources to surface water.

The near-surface portions of the Duluth complex have been weathered, although weathering may be limited in areas scoured by glaciers. Weathering develops fractures, which tend to be concentrated near faults (Stark 1977). Surface lineaments in the Gabbro Lake area trend northeast, so the fractures that form along them also trend northeast with a higher conductivity than surrounding bedrock. Slug tests showed that conductivity was much higher near the lineaments (Stark 1977). Although highly variable, Stark reported at least one test yielded a conductivity near 0.4 ft/d in a borehole 0.02 miles from a lineament, suggesting at least some high flow pathways through bedrock.

Fractures in plutonic rocks tend be parallel, so the conductivity tends to be strongly anisotropic (Stark 1977). Horizontal anisotropy would cause the primary flow vector, or maximum velocity direction, to be parallel to the direction of maximum conductivity which would be parallel to the lineaments and stream channels, or tend to flow northeast. The pathway for flow within the bedrock would therefore tend toward the northeast from the Birch Lake area.

Groundwater level fluctuations in fractured bedrock demonstrate connectivity of fractures with the surface. For example, a well screened from the base of the surficial aquifer to 250 feet into weathered Duluth formation exhibited fluctuations of up to two feet with a half month to a full month lag time (Stark 1977). This demonstrates that within the area of the well the bedrock has sufficient conductivity to allow percolation to reach deeply within the bedrock. Water levels rise in a fractured rock aquifer only if there are connections among significant portions of the aquifer.

Many older studies determined permeability for boreholes and wells in the Duluth formation around Birch Lake. Barr (2014) summarized conductivity test results prepared from earlier studies, including Stark (1977), as ranging from 9.2x10-8 to 1.4x10-5 cm/s, with a geometric mean of 8.0x10-7 cm/s. That is, 0.0003 to 0.04 ft/d, with a geometric mean of 0.002 ft/d. As averages over open interval lengths, these values are low but not impermeable. Considering that most of the permeability would occur over a very small open interval length, there would be significant preferential pathways through the rock as represented by the borehole slug tests.

The presence of fractures throughout the thickness of many boreholes developed within the Duluth formation near the Polymet mine also suggests that fractures near Birch Lake within the same formation would could provide sufficient permeability to allow contaminant transport. Barr (2014) summarized rock quality data as fractures per foot from over 14,000 bore holes near the proposed Polymet mine. Assuming these data are relevant several miles to the east near Birch Lake, there are greater than 15 fractures per foot in some boreholes extending to 500 feet below ground surface (bgs). Barr notes that the average fracture density decreases to less than 1 per foot by 40 feet bgs, but they ignore the variability that shows a much higher density at spots, with many boreholes having much higher fracture density. Thus, there are at least isolated high fracture (and high permeability) zones at least 500 feet bgs. There is no publicly available concomitant data near the Twin Metals lease sites (Figure 1).

Inflow to underground mine shafts is the best way to assess potential pathways at depth. Barr (2014) describes seepage from underground mine facilities in the Duluth Complex that used fracture grouting to control seepage. They referred to four individual fractures that were encountered during the development of a 1700-foot deep exploratory mine shaft at AMAX as producing up to 25 gpm as much as 1194 feet bgs. Grouting reduced inflow to less than 4 gpm and from 9 to 14 gpm for the shaft. Twin Metals (2014, p 19) indicated that 1.9 million gallons of water existed in the Inco Shaft, near their leases, which took three to four months to pump out. After doing so, they expected an additional 70,000 gpd of pumpage, or 49 gpm. If the fractures in either of these shafts were not connected over a long distance, they would have drained so that the flow emanating from them would have approached zero with time. The fact the fractures do not cease flowing means they do not drain and are not empty. That also means they are extensive which indicates they could provide a long-distance flow path for contaminants released at depth.

**Qualitative Risk Assessment for Fracture Flow**

Myers (2016) simulated groundwater flow and transport from deposits in the Rainy headwaters to surface water that flows into the BWCAW. Simulations included leaks on the surface and sources that could result from groundwater flowing through waste that has been backfilled into underground workings. The modeling was completed at a reconnaissance level to assist in broad planning. It does not consider the details of the mining beyond approximate locations of facilities and locations of potential leaks. It assumes there would be engineering failures, which occur sooner or later in most facilities. Foth (2017) criticized the model for not being specific or based on detailed mine site data. This is because such data is not yet available. The intent of the modeling effort was to provide a technique to help decide whether mining is appropriate in a given area; if the risk is too high or the value of the resources potentially affected are too great, the area should not be considered for development.

The contaminant does the most damage during dry periods when it is least diluted. Whether mining in the Rainy headwaters would cause pollution damage in the BWCAW depends on two factors – whether there is a release of contaminant and whether there is a groundwater pathway to surface water. For this analysis, I assume that a leak occurs; assessing this risk is beyond the scope of this memorandum, but most mines ultimately leak.

Myers (2016) estimated flow from surface leaks would reach the rivers in as little as one year with the majority within 100 years. However, his model was based on more isotropic conditions than are indicated by large range in K just noted, so his estimates of breakthrough times are probably high, meaning actual transport times could be much faster. Narrower pathways would allow for less dilution so the load reaching the river could be much larger than estimated by Myers.

In bedrock, groundwater flow through fractures is much faster than general Darcy flow because of the smaller area within fractures to accommodate the flow. Myers (2016) simulated short breakthrough times for contaminants to reach rivers even for contaminants released as deep as 750 meters bgs, although the bulk of the transport required between 100 and 800 years. The times would be substantially shorter if the narrow preferential flow pathways were accurately represented. Rivers were the ultimate sink for most discharges regardless of depth. Contaminant release at depth would contaminate downgradient waters for centuries.

Some geophysical and hydrological methods can be used to infer a connection along pathways between wells, but they cannot prove there is no connection. The methods are most effective for very shallow fractures as represented by closely spaced boreholes. Pump tests are most effective way to test connectivity, but even they cannot prove there is no connection anywhere. If pumping a specified well completed in a fracture does not cause drawdown in another well completed within a fracture, it means there may be no connection between those fractures; it does not obviate the potential connection among fractures throughout a fracture system. A similar point applies to tests of connection between two wells; failure to demonstrate connectivity does not prove there is no connectivity.

The geophysical tests do not apply at depths. Hydrologic tests, such as pump tests, can apply at depth, but only if a system of wells have open intervals through the same interval. It is leaks at depth that may provide the greatest threat of contaminants reaching surface water.

Myers concluded his 2016 paper with the following observation.

> Groundwater with substantial contaminant concentrations discharges to streams whether sourced from deep underground or the ground surface. Even relatively short-term leaks on the surface could cause substantial loads to reach the rivers and valuable downstream resources. Longer-term leaks could cause peak concentrations reaching the rivers to be much higher than simulated herein. Underground sourced contaminant discharges last longer but have lower concentrations and are recommended for use in sensitive watersheds globally. In the Birch Lake watershed, leases trending southwest to northeast would discharge to surface water relatively quickly. Leases in the headwaters of the Stony River watershed would discharge to nearby surface water. These discharges would eventually coincide with critical low flow periods and cause potentially significant damage to rivers and the BWCAW.
>
> Leaks into groundwater commence a long-term process in which contaminants travel to surface waters for a long time after the leaks have ceased discharging. Contamination may not be obvious until after a mine closes and impacts can continue for decades, with substantial concentrations still reaching rivers for hundreds of years even if the leaks cease. These factors should be considered when establishing bonds for long-term water quality remediation and modeling such as presented herein can be used to estimate the potential for future remediation. (Myers 2016, p 288)

Unless there is strong evidence for attenuation, transport should be treated as conservative (Myers 2016); it is not proper to rely on assumptions for preventing downgradient damages. Because transport is through fractures, there would be very little actual contact with carbonate rock so buffering would be minimal.

## Conclusion

The conclusion is that mining in the Rainy headwaters presents a substantial risk to water quality in the BWCAW. The risk is from spills on the surface, leaks from surface storage of waste, even temporary stockpiles, and from seepage through buried waste. Geophysical analyses of boreholes cannot provide evidence of a lack of connectivity through the bedrock to the surface. It is not possible for video of boreholes to show the length of fractures to show their lack of connectivity.

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