In situ Characterization and Deep Borehole Instrumentation to Identify Permafrost Zones at Raglan Mine, Nunavik, QC, Canada

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ABSTRACT

A combined geomechanical and hydrogeological field program, designed to support mining, was developed to investigate permafrost conditions at Raglan Mine (Quebec). Identifying the locations of potential taliks and the depth of permafrost is important for underground mines that penetrate the permafrost as even limited groundwater seepages into the mine can cause ice related operating hazards. The executed field program included in situ hydraulic permeability testing at the transition zone and below the permafrost, geomechanical characterization of the rock mass, laboratory strength testing, as well as the installations of vibrating wire piezometers and thermistor strings in boreholes at depths up to 738 m. The combination of subarctic climate conditions and aircraft cable payload limits required the development of innovative techniques to meet the project objectives. This paper highlights the innovative techniques used to install the instrumentation, summarises the main limitations of traditional installation methods in cold climates, and discusses the implications of the results.

RÉSUMÉ

Un programme d'investigation géomécanique, comprenant un volet hydrogéologique, a été développé pour évaluer les conditions locales du pergélisol à Mine Raglan (Québec). En milieu arctique, l'identification de zones de massif rocheux non gelé (taliks) de même que la détermination de la base du pergélisol est essentielle, car même une quantité minimale d'eau souterraine s'écoulant dans la mine peut engendrer des problèmes de sécurité liés notamment à la formation de glace. Le programme de terrain comprenait la réalisation de mesures de perméabilité in situ dans la zone de transition et sous la base du pergélisol, la caractérisation géomécanique du massif rocheux, des essais de résistance mécanique en laboratoire ainsi que l'installation de piézomètres à cordes vibrantes et de chaînes de thermistances dans des trous de forage aux diamants (jusqu'à 738 m de profondeur). Des conditions climatiques subarctiques jumelées à un accès au site uniquement aérien a nécessité le développement de techniques d'installation innovatrices pour répondre aux objectifs du projet. Cet article résume les techniques innovatrices utilisées dans le cadre du programme d'instrumentation, présente les principales limitations des méthodes traditionnelles d'installation dans les climats froids, et discute de l'implication des résultats obtenus.

1 INTRODUCTION

Two Mining Projects (MP), Donaldson and 14, are presently under study at Raglan Mine, owned and operated by Glencore plc, in order to sustain production and extend mine life. One of these projects may penetrate through the base of the permafrost to depths where groundwater seepages can occur.

In order to support underground mining to depths of greater than 700 m and assess the hydrogeological settings of the future mine workings, a combined geomechanical and hydrogeological site investigation was undertaken in 2015. The specific project objectives included at MP Donalson locating a potential lake talik near a crown pillar area and assessing the potential for groundwater seepages from isolated taliks along fracture zones. The objectives for MP 14 were to locate the base of the permafrost as well as assess the hydraulic conductivity at the transition zone and determine the rock properties for mine design. Key limitations on the project were the requirement to complete all the work within a three month time period during the winter of 2015 with an award date in December 2014, and a logistical restriction that all equipment required must either be onsite already or flown in on commercial flights.

1.1 Site Location and Climate

Raglan Mine is located at the northern tip of the Ungava Peninsula in the Province of Québec (QC), at about 1,800 km north of Montréal (Figure 1). As shown in Figure 1, it is found in a continuous zone of permafrost, where the estimated depth is greater than 500 m (Lemieux, 2016).

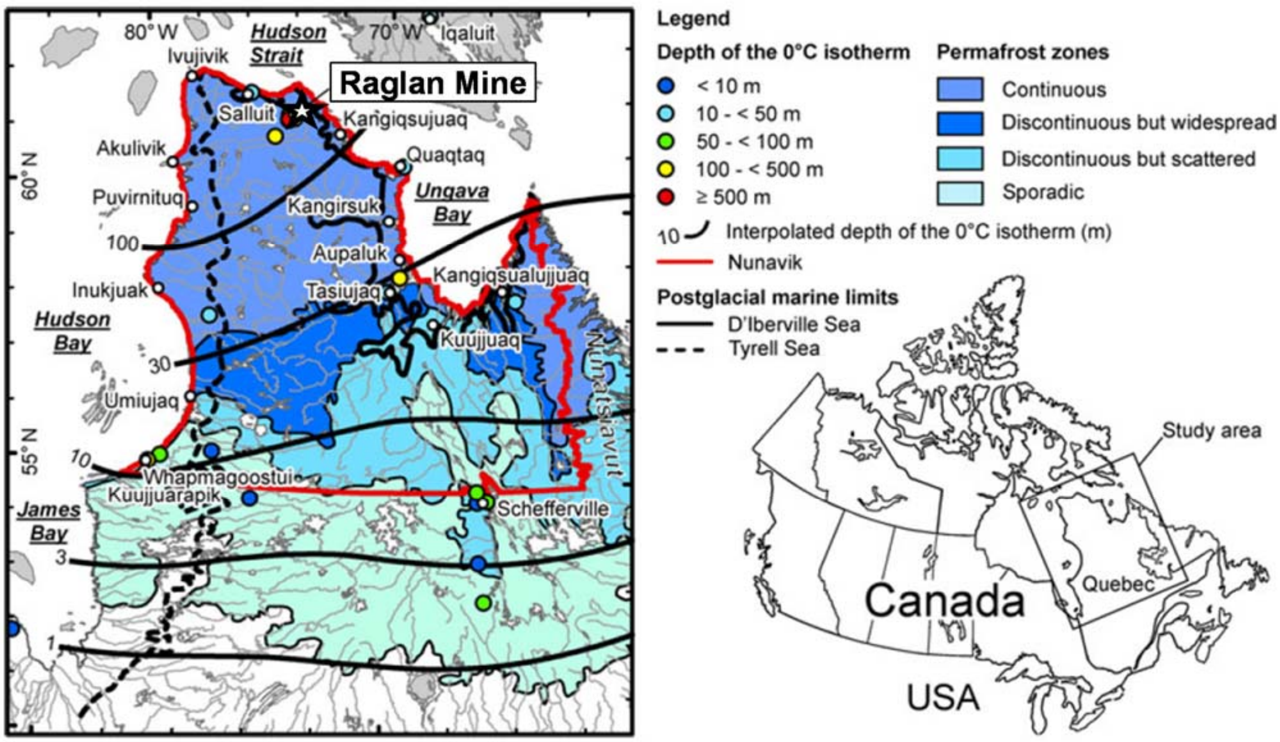


Figure 1. Project Site Location and Permafrost Zones in northern Québec, Canada (after Lemieux et al. 2016)

Subarctic climate conditions that exist at the site are characterized by an average annual air temperature of - 10°C. Local water bodies include the Puvirnituq River and some small lakes that, according to previous drilling records, did not freeze to bottom during winter.

1.2 Geological Setting

At Raglan Mine, metamorphosed sedimentary and igneous rocks form the local geology (Figure 2). The immediate footwall rocks are usually characterized by various Gabbros, while the hangingwall rocks are essentially composed of Ultramafics, Komatiitic Basalt and Metasediments.

The deposit occurs in a sulphide rich mineralization which is normally found in Ultramafic rocks such as Peridotite, Olivine Pyroxenite, and Pyroxenite (shown in red in Figure 2). For the zones specifically under study, the ore body is found at depth greater than 200 m below ground surface, and in some locations, remains open to 700 m.

At MP Donaldson, the deposit is either encountered as thin mineralized lenses, with strike lengths varying from 50 to 200 m, or massive bulk zones. On the other hand, much bigger lenses are observed at MP 14, showing strike lengths reaching up to 450 m.

In both locations, lenses strike essentially east-west and dip north in average at about 40 to 60°.

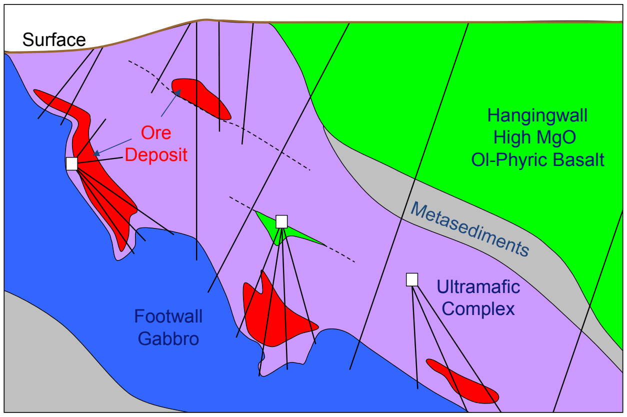


Figure 2. North-South Geological Cross section, looking West, typical of existing Raglan Mine workings (Glencore, 2012)

1.3 Scope of Work

The 2015 geomechanical and hydrogeological field investigations consisted of the following tasks:

- Geomechanical logging of 13 non-oriented NQ sized holes, where 5 holes were located at MP 14 (366 m) and 8 at MP Donaldson (798 m);
- Selection of rock core samples for laboratory strength testing of 270 specimens;
- Rock mass characterization assessment through geomechanical logging, laboratory testing and additional acoustic televiewer surveys (1,781 m);
- Supervision of drilling operation during packer testing using a water inflation system;

- Determination of hydraulic conductivities at specific locations (fault, transition and below permafrost zones); and
- Installation of borehole instruments (thermistors and vibrating wire piezometers) to develop thermal profiles for use in assessing permafrost conditions at depths ranging from 10 m to 738 m below the ground surface.

The location of all borehole collars of interest at MP 14 and Donaldson, which have been either logged, tested or instrumented by Amec Foster Wheeler or others (718-1797, Fortier, 2006) and reviewed for comparison purposes are shown in Figure 3. The Puvirnituq River flows from south to north at the MP Donaldson site.

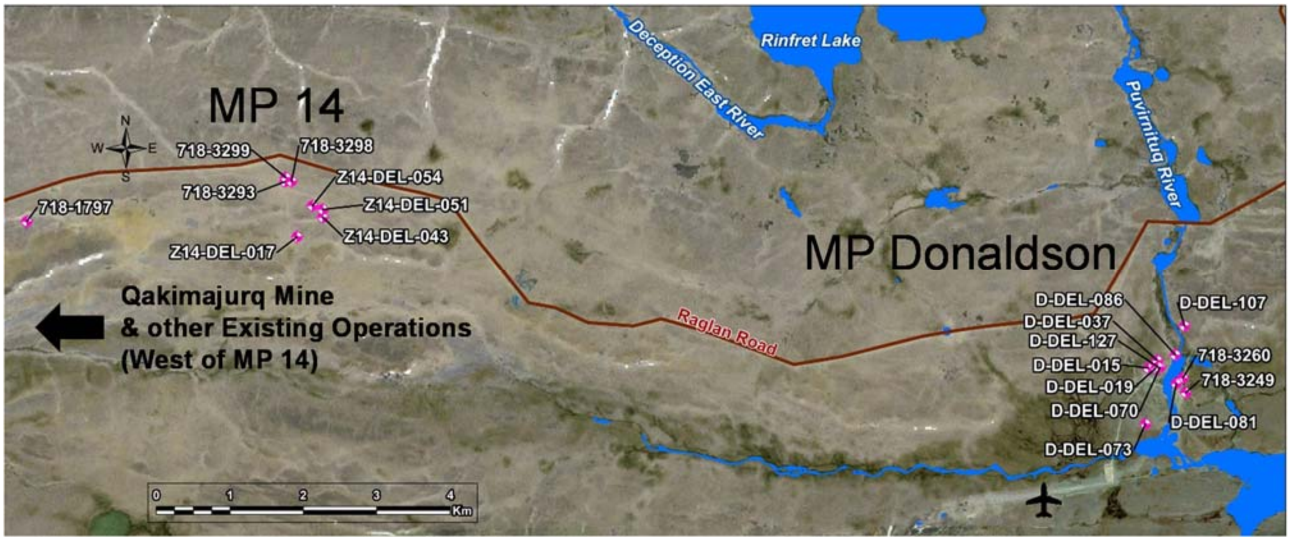


Figure 3. Borehole collar locations, Raglan Mine, QC (Topographic data, Quebec government, 2010)

2 FIELD PROGRAM

To fulfill the objectives of both investigation programs, geomechanical core logging, deep borehole packer testing and borehole instrumentation were performed. Diamond drilling (Figure 4) was performed by Major Nuvumiut JV.

Figure 4. Exploration Diamond Drill Rig, Raglan Mine, QC

2.1 Geomechanical and Structural Data

The geotechnical data collection consisted of the assessment of the following parameters, along with the usual borehole coordinates, orientation and rock type:

- Core recovery and Rock Quality Data (RQD) (Deere, 1989);
- Fracture count and fracture frequency per metre;
- Rock strength and weathering (ISRM, 1978);
- Discontinuity depth, type (joint, contact, fault, shear or mechanical break) and orientation; and
- Joint roughness (Jr), and Joint alteration (Ja), (Barton et. al., 1974, modified AMEC, 2009).

Geotechnical core logging was carried out at site for each 3 m re core run through the zone of interest, while discontinuity parameters were determined for individual features. As the core logged was non-oriented, feature orientation data was collected by acoustic televiewer surveys (Semm Logging, 2015) in the same holes to assess the main joint sets per rock type for both Mining Projects.

Laboratory tests were also performed to assess intact rock strength (Amec Foster Wheeler, 2015). A total of 130 specimens were tested for uniaxial compressive strength (UCS), 107 for Brazilian or splitting tensile strength (BT), and 33 for triaxial strength at three different confinement pressures (5, 10, 15 MPa) to obtain intact failure envelopes of the various units. Hoek and Brown (1980 and 2002) and Mohr-Coulomb failure criteria were computed and compared. In addition, 67 of the 130 UCS samples were instrumented to assess elastic constants such as the Young’s modulus (E) and Poisson’s ratio (ʊ). Finally, densities were calculated on all samples prior to testing. Previous laboratory testing, by Laval University (Grenon, 2014), at MP Donaldson and MP 14, has also been reviewed and incorporated in the current assessment.

2.2 Packer Testing

Packer testing was carried out in three boreholes (718-3298, 718-3293 and D-DEL-127) using NQ sized SWiPS (Standard Wireline Packer System) packer equipment from Inflatable Packers International (IPI) in a single packer configuration. In the SWiPS system the packers are hydraulically inflated through the drill string, eliminating the need for high-pressure gas bottles and inflation lines. The system also provides the capability of carrying a pressure transducer down to the target zone in order to record pressure variations from the test interval down to depths of 1,000 m. The methodology used is briefly described below and illustrated in Figure 5.

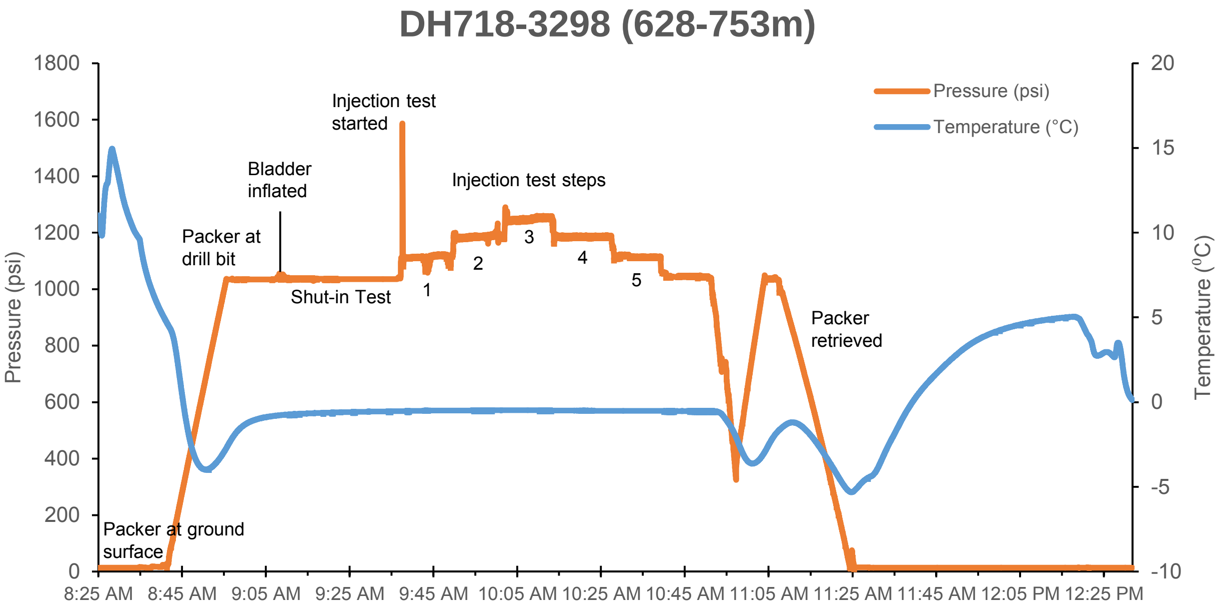


Figure 5. Typical Steps in a Deep Packer Test (SWiPS) at Site

Once the drill rods are positioned at the target depth, the packer system is assembled and inserted into the drill string. The rods are then filled with brine, and the water level at the top of the rods is monitored to determine any significant leakage. The packer is then hydraulically inflated until the pressure causes shear pins to fail, and open a valve to the lower section. When a proper seal is obtained, water (in this case brine) is allowed to flow through the system while the pressure and flow is monitored for a period of 10 to 20 minutes (shut in test), varying the pressure and flow to confirm the proper functioning of all system components.

The constant head test is then carried out by measuring the amount of flow, using a flow skid (housing pressure gauges and a flow meter), while maintaining a constant pressure at three increasing and two decreasing pressure levels for a total of 5 steps each of 10 minutes duration. At each step an initial volume, intermediate volumes taken at one minute intervals and a final volume after 10 minutes, are read from the flow meter and recorded.

Following the collection of pressure and flow data from the constant head test, the pressure is released to stop the flow. The wireline is lowered and connected to the packer, which is pulled up to break shear pins thus causing the packer to deflate.

Because the rock mass was tight, pressure levels used in the packer tests performed at site were determined based on the target depths and the amount of flow observed at various pressures. Where leakage was observed on surface, the amount of flow was measured and subsequently used to correct the hydraulic conductivity for the test interval.

The packer test results were analyzed using the pressures recorded in the downhole transducer as the injection pressure was applied. A correction factor for fluid viscosity using brine concentrations measured in samples of the brine taken from the drilling site was then applied. The estimated brine density was 1.22.

2.3 Borehole Instrumentation

Borehole instrumentation included both vibrating wire and thermistor string installations.

2.3.1 Traditional Installation Methods

In less remote areas, downhole instruments are typically installed using methods developed for standpipe piezometers (Dunnicliff, 1988, 1993), where instruments are surrounded by a poured-in sand pocket with a bentonite seal above, or are fully grouted in place with a cement-bentonite grout (Mikkelson and Green, 2003). However, this approach is not suited to deep installations in remote sites because the costs and time required to bring supplies and equipment to the site are cost prohibitive and logistically impractical in a short time frame at fly-in only locations. Grouting of instruments at depths below 500 m in a brine environment requires specialized cement mixes, and would have required special pumping equipment not readily available at site.

In some northern areas, such as Plateau Katinniq (Nunavik, Québec), where Raglan Mine site is established, thermistor strings have been installed, in steel pipes (1″ diameter) filled with silicon oil at depths up to 430 m (Fortier, 2006). In this method the pipe is first installed across the length of the borehole and filled with silicon oil. A thermistor string is then lowered down the pipe in stages, being allowed to reach equilibrium and measured at each stage until a thermal profile of the hole is collected. Again, in order to remain cost efficient when performing several installations at depth in a relatively short time period, this method could not be used. Furthermore, considering the amount of steel casing and oil that would need to be airlifted to the site, this approach was impractical. Also, the pipe diameter is a limiting factor when several strings are required to be installed permanently in the same borehole. Finally, this installation method would not be appropriate for vibrating wire piezometers, as the instrument is physically isolated from the borehole walls, and consequently not in contact with surrounding ground waters.

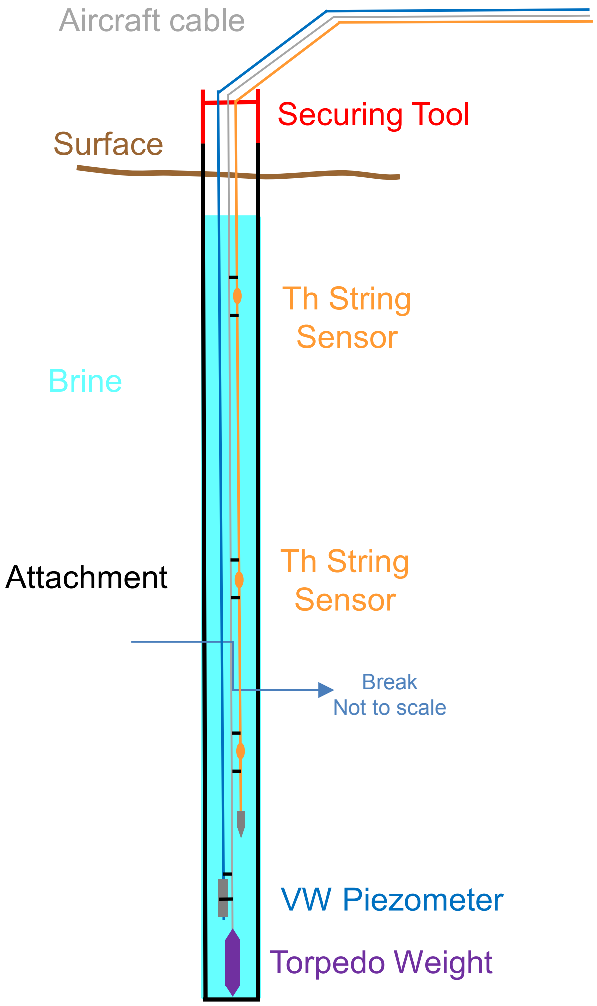
Another method of thermistor installation is the installation of thermistor strings in existing open boreholes, which are then allowed to freeze. This approach has been performed in open boreholes up to a depth of 450 m at several mine sites in the Cape Smith – Wakeham Bay Belt, in Northern Québec (Taylor and Judge, 1979). In these cases, thermistor cables containing up to 20 thermistors, were lowered into exploratory diamond-drill holes upon completion and allowed to freeze in place. This approach has the advantages of being relatively inexpensive and having few logistical demands. The method is limited by the strength of the thermistor cables themselves to hold the weight of cable needed for deeper installations, and where multiple sensors are required, by the pressure rating of the instrument string as a whole.

The pressure rating of the thermistors is a critical consideration when working with very deep, fluid filled holes, and in particular denser brine filled holes. While not specified in the paper of Taylor and Judge (1979) nor in Fortier (2006), the fact that both studies were limited to depths of approximately 430 to 450 m suggests that this was maximum depth that could be reached within the survivable pressure range of the equipment. Most commercially available thermistor strings are rated to 3.5 MPa, which is equivalent to 350 m or less of submergence, although conservatism in the design usually allows for deeper installations.

2.3.2 Innovative Techniques

The approach taken at Raglan Mine for this project was a modification of the method described by Taylor and Judge (1979). For Raglan Mine this method required modification to: 1) allow for installation to depths of greater than 700 m in angled holes and 2) allow for the installation of multiple thermistor strings and vibrating wire piezometers so that equipment with higher pressure ratings could be installed. The modifications applied included the attachment of the instruments to a central stainless steel aircraft cable which was kept taut by a torpedo weight (Figure 6) with an approximate weight of 7 kg. The use of a torpedo weight cable system was considered necessary to: a) maintain the cable in a taut condition to allow for an accurate understanding of the depth of installations, b) allow for installation in the angled boreholes available for this project without instruments becoming caught on the side of the borehole and c) share the load of the instrument weight.

Figure 6. Deep borehole Schematic Installation in an open hole filled with brine



The aircraft cable was selected to be capable of taking the majority strain that would otherwise be applied to the instruments themselves by their own weight allowing for deeper installations (some thermistors strings have a 50 kg weight restriction). By taking the strain created by the weight of the instruments themselves, the cable was also able to support multiple instruments in the same borehole. This is critical where individual instruments were required to be installed at depth due to the pressure limitations of most thermistor strings. As a result of the use of the aircraft cable, a combination of thermistor strings, thermistor probes, and vibrating wire piezometers could be installed over depth ranges from surface to greater than 700 m within the same, angled borehole.

Finally, unlike the method of Taylor and Judge (1979), which assumed the thermistors would freeze in place because the boreholes used were entirely within permafrost, this project faced the additional concern that where the boreholes pass through the base of the permafrost, there could be fluid movement within the hole creating a circulating thermal system. The opportunity to conduct packer testing below the permafrost allowed for confirmation of whether potential fluid movement was a concern.

Photos from a typical deep borehole installation are shown in Figure 7 while a brief methodology is provided below.

Figure 7. Instrumentation in Deep Boreholes: a. Air craft cable spool, b. Instrumentation cables at collar with securing tool, c. Thermistor String Sensor, d. Vibrating Wire Piezometer

Prior to installation, instruments were checked to ensure proper function and boreholes assessed for any potential blockages. In order to handle the various instrument spools at the surface, metal stands were used.

The aircraft cable was attached to the bottom of the wireline and run through the rig hoist. Different techniques, such as mechanical attachments, were used to secure the instruments to the aircraft cable, as they were lowered down the hole to their specific depth. Tapes were also used to ensure smoothness of the attachment points. Once the instruments were lowered to the required depths, they were finally secured to the top of the casing using a specially design tool (see Figures 6 and 7). On surface, instrument cables were protected against severe weather and wildlife using protective conduits and metal cabinets facilitating the data acquisition.

3 FINDINGS

Due to geographical location, and distinction in deposit geology, MP Donaldson and MP 14 were characterized separately.

3.1 Joint orientation, Intact Strength and Rock Mass Classification

To maximize the statistical analysis of the geomechanical data, it was decided to group the results per domain, as follows:

- Domain 1, MP Donaldson South, for the most part made of inclined tabular lenses;
- Domain 2, MP Donaldson North, for the most part formed by various bulk zones; and
- Domain 3, MP 14, for the most part, comprised of inclined tabular ore lenses.

Figure 8 shows a typical pole plot obtained from acoustic televiewer surveys (Semm Logging, 2015). In this case, the ore zone (OZ) of Domain 1, encountered at a depth of 15 to 370 m deep, is shown. It indicates that four main joint sets were encountered:

- Set 1, foliation set dipping at 49° to the north east following the main trend and dip of the ore body, is indicating a sub-parallel dipping set to the plunge and strike of the ore zone.
- Set 2, north-south set, dipping at 55° to the west,
- Set 3, sub-horizontal set, dipping to the south at 39° and almost a conjugate to Set 1.
- Set 4, north-south set, dipping at 57° to the east, and a conjugate to Set 2.

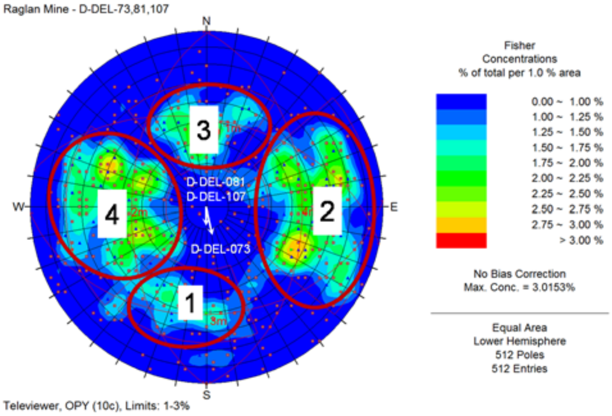


Figure 8. Stereographic Projection, OZ (10c), Domain 1

Locally, some variations are observed from one domain (1 to 3) to the next, but overall, the joint sets presented in Figure 5 are representative of all ore zones of the deposit. As for the other mining zones, the jointing appears to be similar to the OZ in the hanging wall (HW) and less fractured in the footwall (FW), with a respective joint number or Jn (Barton et. al., 1974) of 12 and 6. Mining zones were defined according to the Glencore geologist's interpretation on a borehole basis.

The average rock mass ratings (Bieniawski, 1976, & 1989, Hoek and Brown, 1980) obtained from geomechanical core logging and televiewer surveys, are summarized per domain and mining zones in Table 1.

Overall, no significant variation of the rock mass properties have been observed across the deposit, with an average RMR'89 comprised between 70 and 75, which correspond to a \`Good\` quality rock mass.

Table 1. Summary of Average Rock mass ratings

Domain #	Zone	Q\` -	RMR'76 (%)	RMR'89 (%)	GSI (%)
1	HW	17.50	69	75	70
	OZ	15.27	68	74	69
	FW	13.24	66	72	67
2	HW	12.87	67	72	67
	OZ	15.08	68	78	73
	FW	15.00	67	75	70
3	HW	15.26	68	72	67
	OZ	17.95	69	73	68
	FW	22.00	70	70	65

The mean values of the laboratory tests performed are summarized in Table 2. Again, for all domain and mining zones tested, the rock appeared to be very strong, with an average UCS comprised between 200 and 261 MPa, with the exception of the ore zone of MP 14 (355 MPa), that was extremely strong (ISRM, 1978).

Table 2. Summary of Average Intact Rock Strength

Domain #	Zone	UCS (MPa)	BT (MPa)	E (GPa)	ʊ -	Density (kg/m^3)
1	HW	227	18	68.9	0.33	2926
	OZ	209	16	67.1	0.30	2888
	FW	233	19	64.4	0.34	2879
2	HW	200	14	71.8	0.32	2858
	OZ	217	17	57.8	0.27	3055
	FW	198	15	63.8	0.37	2957
3	HW	261	19	83.7	0.27	2886
	OZ	355	19	74.6	0.31	3106
	FW	195	19	85.9	0.26	2972

3.2 Potential taliks and base of the permafrost

A graph of the combined thermistor results is provided in Figure 9. Also shown, are some additional temperature data collected by Université Laval in 718-1797, situated about 3 km west of MP 14, using the methodology described earlier in this paper (Fortier, 2006). For reference, the location of boreholes is shown in Figure 3. Table 3 includes a summary of the borehole details.

Table 3. Summary of borehole details with thermistor installations (see Figure 3 for BH location)

Borehole ID #[1]	Surface elevation (masl)	Dip (°)	Total length (m)
D-DEL-070	571	-84	306
D-DEL-073	570	-77	81
D-DEL-086	568	-72	417
D-DEL-127	572	-84	252
718-3293	646	-83	750
718-3298	646	-83	753
718-3299	647	-84	756
718-1797	614	-75	545

[1] D is for Donaldson, DEL for Delineation, 718 series is for MP14

With the exception of the results from borehole D-DEL-086, all the boreholes show consistent temperature trends with depth, in that from surface down, all the temperatures reduce to a minimum at depths of about 60 m to 100 m before slowly increasing again.

In the measurements from the deeper instruments, the results show a small increment of approximately 1.2 degrees per 100 m from 100 to 700 m below ground surface. There is, however, some local variation in the temperature profile that is possibly related to the presence of differing geology. In particular, it appears that the presence of argillite in the bedrock can act as an insulator and locally deflect the temperature curve.

In the deepest borehole equipped with thermistors, 718-3299 (MP 14), the base of the permafrost is located approximately 685 m below ground level based on the available measurements and assuming the groundwater does not contain sufficient salt to shift the freezing point below 0 degrees.

The results from D-DEL-086 appear to be an exception to the general trend described above. The temperatures in this hole are several degrees Celsius higher than the other boreholes. While the measurements of temperature remain below 0 indicating permafrost, the relatively high temperatures suggest the presence of a nearby talik (not a through talik) either now or in the recent geologic past.

The above average temperatures observed in borehole D-DEL-086 are possibly influenced by the presence of a nearby lake.

Ongoing pressure readings from the vibrating piezometers indicate that equilibrium conditions have not been reached at the time of writing of this paper. Additional readings are being taken about twice a year to monitor *in situ* conditions.

3.3 In situ Hydraulic Conductivity of Bedrock within or below Permafrost

In situ hydraulic conductivity measurements were made within or below the permafrost at three boreholes using the packer test methodology described earlier. Two packer tests were performed at each of the three boreholes tested. The results of are summarized in Table 4.

Table 4. Summary of Packer Test results

BH -Testing Interval (m)	Rock Type (1)	k (m/s)
D-Del-127 (66-306m)	4a, 10d, 10b, 4f	1.8x10^{-10}
D-Del-127 (111-306m)	4a, 10d, 10b, 4f	7.0x10^{-11}
718-3293 (631-750m)	10d, 9a	6.3x10^{-9}
718-3293 (400-750m)	6a	4.5x10^{-10}
718-3298 (628-753m)	10d	2.4x10^{-9}
718-3298 (400-753m)	6e, 6a	4.3x10^{-10}

(1): 4a:Argillite, 4f:Hornfeld Sediments, 6a:Massive Flow, 6e:Agglomerate Breccia, 9a:Normal Gabbro, 10b:Peridotite, 10c:Olivine Pyroxynite, 10d:Pyroxynite

The results indicate that the measured hydraulic conductivities (k), when averaged out over the length of the packer test interval, are very low, which is consistent with

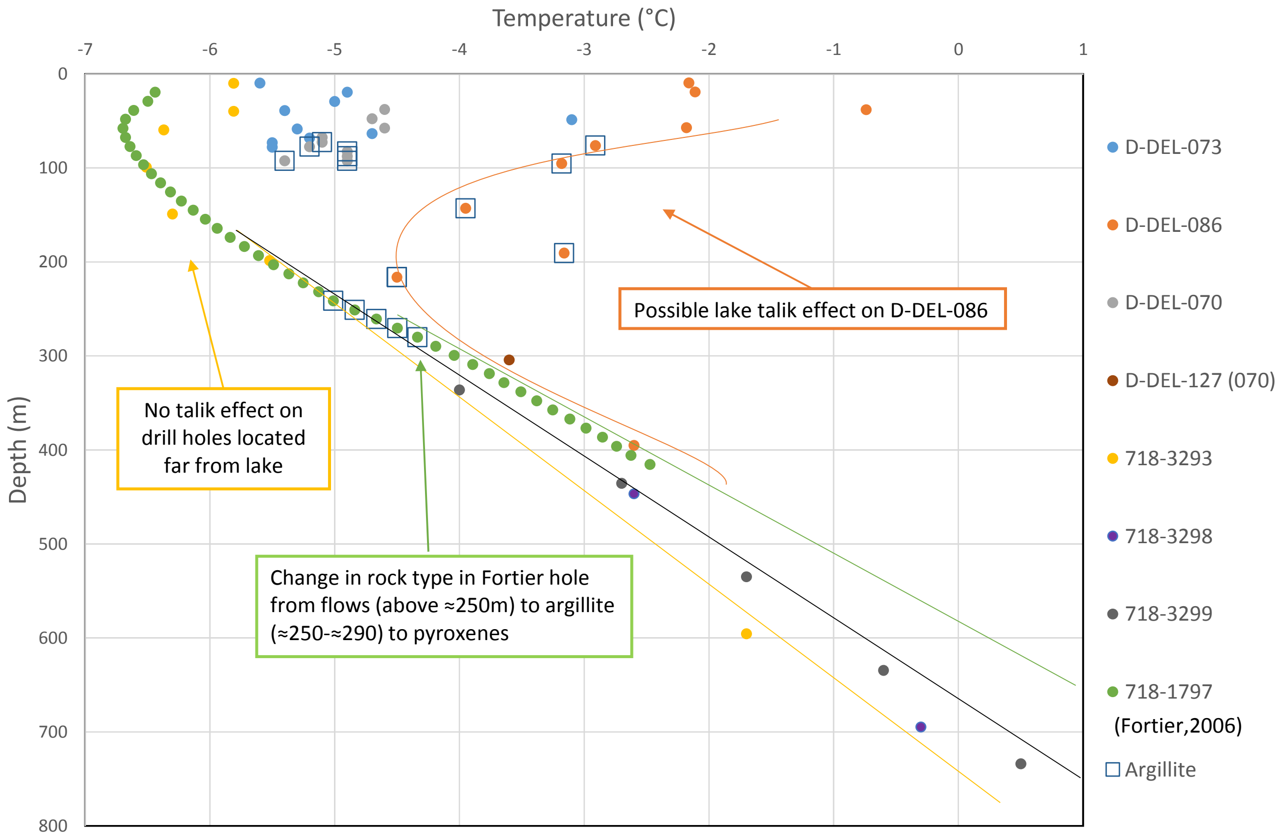


Figure 9. 2015 Site Temperature Data versus Depth (Temperatures measurements taken between three days to two months of installation)

the expected hydraulic conductivity results in deep bedrock or permafrost.

The tests in D-DEL-127 were conducted entirely within the permafrost zone, but adjacent to a borehole (D-DEL-070) which had collapsed at a potential fault zone.

The collapse of material at this fault zone was thought to indicate potential for brine fluid within a fracture, but the very low hydraulic conductivity of the rock suggests that either this fault was not intercepted by D-DEL-127 (within the permafrost) or that the fault is frozen and not fluid bearing.

The packer tests in 718-3293 and 718-3298 were conducted to investigate the hydraulic conductivity of the bedrock at the transition zone and/or below the permafrost. The concern here was that freeze-thaw cycles created by the upwards and downwards migration of the permafrost base may have fractured the bedrock resulting in a zone of higher than expected hydraulic conductivities.

The results of these tests indicated that the hydraulic conductivities in the deeper test intervals were slightly higher than in the shallower test intervals that encompassed more of the permafrost zone. This suggests that the hydraulic conductivity of the lower part of the holes was higher than in the upper part of the hole, suggesting the hydraulic conductivity increases where the borehole extends into unfrozen rock below the base of the permafrost.

At this depth, the thermal profiles suggest that only the lower approximately 50 m of the two deep holes penetrate below the permafrost. If it is assumed that all the transmissivity of the bedrock occurs only in this interval, the estimated hydraulic conductivity of the unfrozen portion of rock can be estimated by prorating the results from the packer test interval to a 50 m interval. Applying this method to the deepest packer tests from each borehole, the estimated hydraulic conductivity of the upper 50 m of unfrozen bedrock beneath the permafrost is 9.5×10^{-9} m/s. This is again a relatively low permeability and agrees well with the typical decrease with depth in non-permafrost zones and the “Good” rock mass quality.

4 CONCLUSIONS

The results of the 2015 site investigation programs were able to meet the objectives of both Mining Projects at MP Donaldson, locating a potential lake talik (not a through talik) near D-DEL-086 and assessing hydraulic conductivities within the permafrost near a potential fault zone (D-DEL-127) and; at MP 14, identifying the base of the permafrost (≈ 685 mbg assuming low solute concentrations in groundwater), as well as assessing the hydraulic conductivity of the rock mass at the transition zone.

Based on the packer testing conducted at MP 14, the estimated hydraulic conductivity of the unfrozen bedrock beneath the permafrost is 9.5×10^{-9} m/s. These results are similar to slightly higher than hydraulic conductivities results at similar depths at other mine sites in similar terrains, suggesting that fracturing due to sub permafrost frost-thaw cycles may have not significantly increased the hydraulic conductivity of the bedrock at this location.

The rock hydraulic conductivity is, however, sufficient to suggest that some limited movement of groundwater can occur along fractures beneath the permafrost. This seepage might initially be significant where confined waters under the permafrost have not been depressurized in advance of mining. As such, there is a potential for groundwater seepage into the mine to be a hazard because the below freezing operating conditions of the mine will result in ice buildup at groundwater ingress locations.

The packer test results also have an implication for regional groundwater flow. The relatively low hydraulic conductivity of the unfrozen bedrock beneath the deep permafrost at Raglan Mine suggests that regional groundwater flow beneath the permafrost between taliks may be limited.

The above results should be considered as preliminary and representative of near borehole conditions. Additional deep borehole instrumentation would be required to confirm the trends along with monitoring of the existent instruments.

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