



Mine Dewatering Wells: Reducing Economic Risk And Increasing The Probability Of Success Through Diamond Drilling

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ABSTRACT

The Iron Ore Company of Canada (IOC) Carol Lake Mine, located in western Labrador, has been operating since 1962. IOC has three shareholders (Rio Tinto, Mitsubishi Corporation, and Labrador Iron Ore Royalty Corporation) and produces iron concentrate and pellets for sale on the international market. Geologically the orebody has been strongly metamorphosed, folded, faulted, and altered resulting in a complex hydrogeologic setting. Much of the orebody is below the water table. Hydrogeologically the orebody is primarily composed of crystalline non-porous/non-permeable rock crosscut by discrete permeable/porous limonitic shear zones. Dewatering wells target these shear zones as they are productive aquifers. However, given the complex geology identifying a productive dewatering well is challenging and, given the expense, high stakes. This paper will examine how diamond drilling was utilized to increase confidence in the In-Pit 15 dewatering well target. Discussion is focused on the conceptualization of the well and its successful outcome.

RÉSUMÉ

La mine de Carol Lake de la compagnie Minière IOC, située dans l'ouest du Labrador, est en opération depuis 1962. IOC a trois actionnaires (Rio Tinto, Mitsubishi et Labrador Iron Ore Royalty Corporation) et produit du concentré de fer ainsi que des boulettes pour la vente à l'international. Géologiquement, le gisement a été fortement métamorphosé, déformé et altéré entraînant la création d'un réseau hydrogéologique complexe. La majorité du gisement est sous la nappe phréatique. Hydrogéologiquement, le gisement est principalement composé de roches non poreuses/non-perméables traversées par des zones de cisaillements discontinues limonitiques perméables/poreuses. Les puits de pompages ciblent ces zones de cisaillements car ce sont des aquifères productifs. Cependant, étant donné la nature géologique complexe de ses zones, identifier un puit de pompage productif est difficile et, du fait des coûts associés, un enjeu important. Cet article examine comment le forage au diamant a été utilisé pour augmenter la confiance dans la cible du puit de pompage numéro 15. La discussion est focalisée sur la conceptualisation du puit et son résultat positif.

1 INTRODUCTION

Carol Lake Mine and associated beneficiation facilities, located near Labrador City, Newfoundland and Labrador (NL) (Figure 1), were opened by the Iron Ore Company of Canada in 1962. Today, IOC has three shareholders: Rio Tinto (site manager), Labrador Iron Ore Royalty Corporation, and Mitsubishi Corporation. Nameplate production capacity is 23 million metric tons per year (Mtpa) of concentrate of which approximately 13.5 Mtpa can be processed into a range of value added pellets. This makes IOC among the leading North American producers and exporters of quality iron ore pellets and high grade (>65% Fe) sinter feed (both of which are sold on the international market).

Currently production targets are achieved through open pit mining five orebodies. Consistent long term ore feed is achieved through detailed geologic, geotechnical, and hydrogeologic modelling of these orebodies. The primary building block of the models is diamond drill core

data. Each year IOC may drill several thousand meters of diamond drill holes (ddh). This paper proposes maximizing value by augmenting diamond drill programs, especially in areas of geologic complexity, to include investigating dewatering well targets. The goal is to construct the most effective dewatering wells possible, in a given orebody, to assist and advance mining.

2 GEOGRAPHY AND CLIMATE

2.1 Location

Carol Lake mine is situated in an established mining district in the western uplands of Labrador. The mine is located roughly 10 km north of Labrador City. Neighboring mines include Scully (Tacora) also in NL, and Lac Bloom (Quebec Iron Ore), and Mt. Wright (Arcelor Mittal) both in the Province of Quebec.

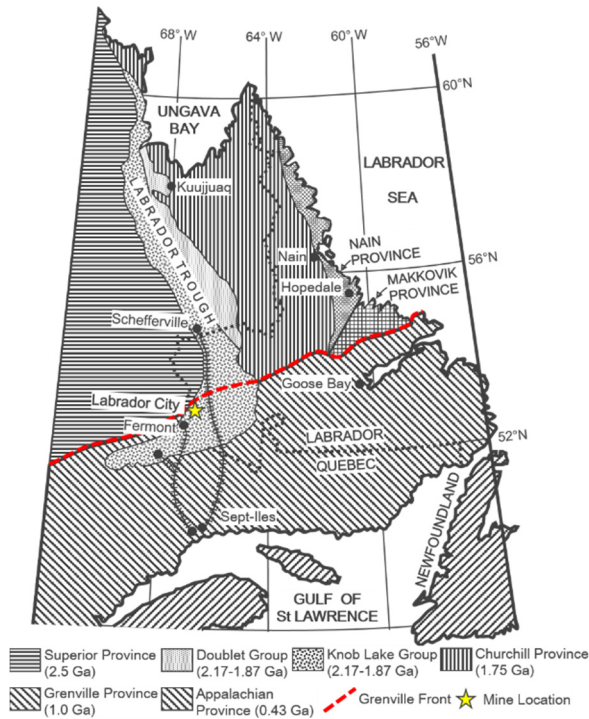


Figure 1. Map showing the location of the mine relative to the Labrador Trough, geologic provinces, and population centers. Note, Ga = billions of years. Modified after Rivers and Wardle (1978).

2.2 Climate

The region experiences a continental subarctic climate (SEM Ltd. 2018). WSP Inc. (2019) summarized climate data from 1981-2010 for the IOC hydrogeologic conceptual model. Average annual precipitation is 840 mm and, due to the cold climate, a significant amount falls as snow (on average 449 cm). The wettest month is normally July (113.9 mm) while the driest month is February (40.3 mm equivalent rainfall).

3 GEOLOGIC SETTING

3.1 Regional Geology

3.1.1 Labrador Trough

The Labrador Trough is approximately 1,000 km long, Proterozoic aged, sequence of predominantly clastic and chemical sedimentary rocks (Neal. 2000) (Figure 1). This sedimentary sequence was originally deposited on a continental margin (Conliffe. 2012) on top of the much older rocks of the Superior Craton. Deposition occurred between 2.17 and 1.87Ga ago (Wardle et al. 2002).

3.1.2 Sokoman Iron Formation

The Sokoman Iron Formation, ranging from 30 to 170 m in thickness (Neal. 2000), is one of the largest

continuous iron formations (IF) in the world (Coates. 2012). It is classified as Lake Superior Type, due to its extent and depositional environment, and contains examples of oxide, silicate, and carbonate facies iron formations.

3.2 Mine Site Geology

3.2.1 Orebody Stratigraphy

All of the ore at Carol Lake occurs within the Sokoman. The three units that compose the formation have been named (at IOC): the Upper Iron Formation (UIF), the Middle Iron Formation (MIF), and the Lower Iron Formation (LIF) (Table 1). The UIF is a carbonate facies iron formation and is largely classified as waste. The MIF is an oxide-facies iron formation and is the primary ore-bearing horizon. Internal to the MIF are a series of discontinuous waste horizons (carbonate, gabbro, and limonite). The LIF is a carbonate facies iron formation and classified as waste. There is a thin and continuous oxide iron formation internal to the LIF.

Table 1. Sokoman iron formation stratigraphic column.

Formation		Primary Rock Types
Menihék		Youngest formation of the Knob Lake Group comprising mainly quartz-feldspar-mica-graphite schist.
Sokoman	Upper Iron Fm. (UIF)	Light brown/white quartz-carbonate (siderite) gneiss with variable amounts of magnetite, hematite, and various iron silicate minerals.
	Middle Iron Fm. (MIF)	Quartz-magnetite, and/or quartz-specular hematite-magnetite, and/or quartz-specular hematite-magnetite-carbonate schist units.
	Lower Iron Fm. (LIF)	Light brown/white quartz-carbonate (siderite) gneiss with variable amounts of magnetite, hematite, and various iron silicate, and/or quartz-carbonate-magnetite, and/or quartz-magnetite-specular hematite units.
Wishart		White massive to foliated quartzite.

3.2.2. Structural and Metamorphic Geology

Carol Lake Mine is located 15-20km south-east of the Grenville front (Figure 1). Correspondingly the dominant deformation features observed are Grenvillian (SRK Ltd. 2018). The Grenvillian Orogeny occurred at 1090-980Ma (Rivers. 2008). Metamorphic grade ranges from garnet-biotite (450°C/600MPa) to staurolite-Kyanite (570°C /800MPa) (van Gool et al. 2008).

SRK Consulting (Canada) Inc. structurally mapped the deformation in several pits at the request of IOC. SRK confirmed three distinctly different phases of deformation, two of which are important from a hydrogeologic/dewatering perspective:

D₂ (Reverse-Fault Zones)

D₂ deformation primarily manifests as brittle-ductile shear zones and NW vergent open to tight fold systems. In Luce Pit, where In-Pit 15 is located, the most prominent D₂ structure is the West Wall Shear Zone

(WWSZ). The majority of dewatering wells, in this pit, target this structure.

D₃ (Strike-slip Fault Zones):

The D₃ system of brittle faults trend north-west, are sub-vertically dipping (75 to 80°), and are late stage. The largest D₃ feature in Luce Pit, named NW Main, is located in the south-east corner of the pit. This feature consists of a band of breccia, up to 60 m wide, and is the target of the In-Pit 15 well.

3.2.3. Limonite Alteration

Limonite alteration (Figure 2), associated with low RQD, is present in varying degrees at IOC. Limonite is a general term for a mixture of iron oxyhydroxides (e.g. 2Fe₂O₃•3H₂O and goethite [FeO(OH)]) with variable physical and chemical properties formed from the oxidation (weathering) of iron bearing minerals (Neuendorf et al. 2005). At IOC limonite alteration is associated with D₂ and D₃ shear zones (propagating down dip to depths >200m) and is strongest closest to surface with alteration intensity generally decreasing with depth. Deep supergene weathering has been proposed as the source of the limonite (Coates. 2012).

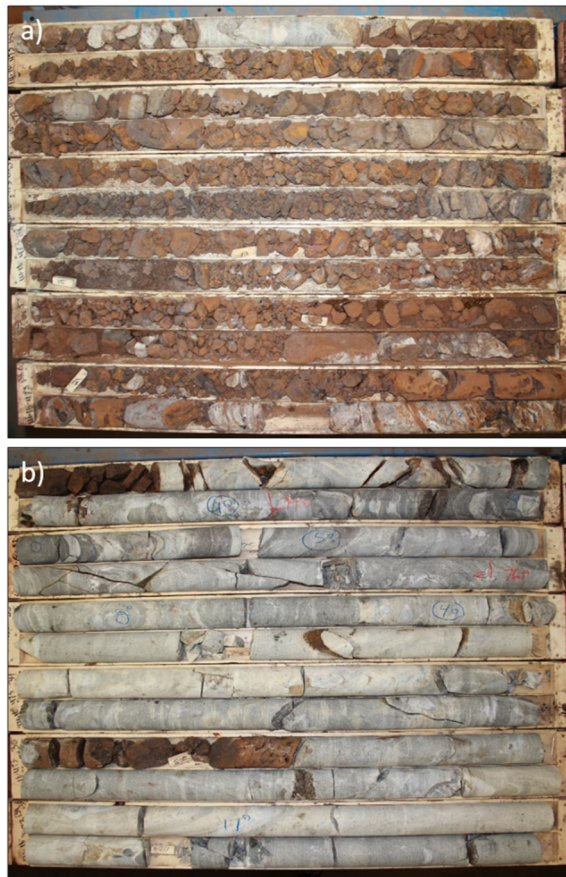


Figure 2. Diamond drill core from hole LU-16-473: a) 2-23m, limonite (brown) altered carbonate IF and b) 72-85m unaltered carbonate IF.

3.3 Hydrogeology

3.3.1 Aquifer Characteristics

Geologic and Grenvillian deformation features dictate aquifer characteristics at Carol Lake (WSP Inc. 2019). Original primary porosity of the sedimentary protoliths was obliterated during metamorphic recrystallization. Secondary porosity was created by fracturing, faulting, and shearing. Supergene weathering, propagated along D₂ and D₃ shear zones, increased the porosity and permeability of the rock creating tertiary porosity. Groundwater flow occurs primarily through secondary and tertiary porosity. Tertiary porosity, in the form of low RQD limonitic altered shear zones, is the most hydrogeologically productive rock and is therefore the main target for dewatering wells where it exists.

3.3.2 Groundwater Flow Direction

Regional groundwater flow in the area (pre-development) is generally toward Wabush Lake. However in the immediate Luce Pit area, groundwater flow in all directions is toward the pit as the pit is actively being dewatered. Water dominantly flows along the north-south striking D₂ and D₃ structures. East-west flow does occur but is estimated to be smaller and focused along crosscutting joints and fractures.

3.3.3 Aquifer Hydraulic Properties

A variety of aquifer tests (airlift, variable pumping rate, and constant pumping) and in-situ permeability tests (packer and falling head) have been used to characterize the hydraulic conductivity and transmissivity values of the aquifer as reported in Piteau (2015 a, b). See Table 2 for a list of average hydraulic conductivities for select lithologies.

Table 2. Hydraulic conductivities for select lithologies.

Lithology	Hydraulic Conductivity (m/sec)	Geometric Mean(m/sec)
Quartz-Carb (n=8)	5 X 10 ⁻¹¹ to 9 X 10 ⁻⁷	4 X 10 ⁻⁹
Quartzite (n=6)	2 X 10 ⁻¹⁰ to 2 X 10 ⁻⁷	4 X 10 ⁻⁹
HMO (n=5)	4 X 10 ⁻¹¹ to 3 X 10 ⁻⁴	7 X 10 ⁻⁹
Limonite (n=4)	3 X 10 ⁻⁸ to 2 X 10 ⁻⁵	6 X 10 ⁻⁷

Specific yields (storativity) are estimated to be roughly 0.02 to 0.03 (Piteau. 2015c) which is consistent with a fractured rock aquifer (WSP. 2019). Specific yield of tertiary, limonitic rock, is estimated to be an order of magnitude higher (WSP. 2019).

Hydraulic compartmentalization is common. Large differences in groundwater surface elevations, hydraulic conductivities and connectivity, and a lack of response to pumping, are observed over short distances. This effect can be seen by comparing monitoring wells MW25 and MW48 (Figure 3).

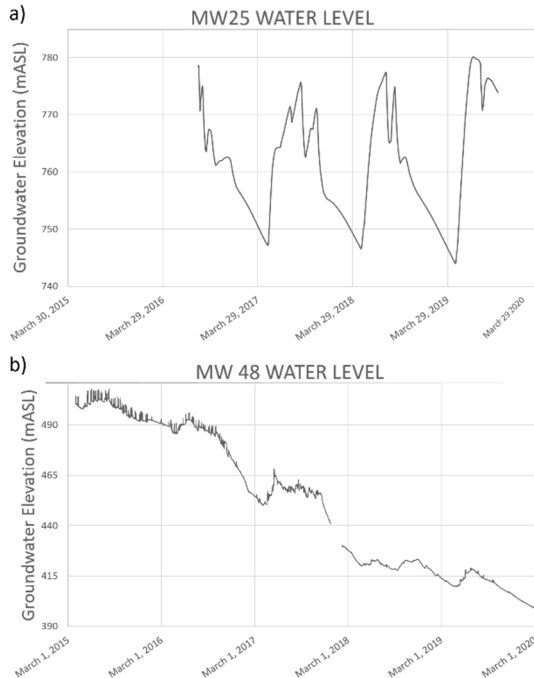


Figure 3. Monitoring wells MW25 and MW48 are located ~730 meters apart in Luce (Figure 4): a) MW25, note the seasonal variation (y-axis is 40 meters), b) MW48, note groundwater drawdown due to pumping influence (y-axis is 120 meters) over 5 years.

3.3.4 Groundwater Recharge

Precipitation and leakage from topographically higher lakes, streams, and bogs all contribute to groundwater recharge (WSP. 2019). Annual aerial recharge rates to groundwater were estimated by Piteau for the site water balance, at 131.3 mm for native soils, 106.8 mm for pits/roads, and 137.0 mm for waste dumps (Piteau. 2011a).

Spring freshet normally begins in mid-April, lasting for two to three weeks, during which time the accumulated winter snowpack melts, runs off and infiltrates into the ground. Melt and rainwater infiltration causes groundwater levels to rapidly increase site wide (except for areas influenced by pumping). Elevations remain high throughout the summer, gradually decreasing through the fall, and decreasing at a faster rate during the winter as freezing temperatures inhibit groundwater recharge (continuing until the next spring freshet) (WSP. 2019).

3.4 Computer Models

Geologic and geotechnical (RQD) models are used to assist with identification of dewatering well targets. Maptek Vulcan software is used to visualize the data.

3.4.1 Geologic Model

Sub-blocked and regularized geologic models are maintained for each deposit. The sub-block model shows fine geologic detail. Identifying preliminary dewatering well targets begins with ascertaining strategic limonite altered horizons and areas of low RQD in the sub-block model.

3.4.2 Geotechnical Model

Geotechnical models are maintained for deposits that are, or soon to be, in production. RQD values are populated for each block based on the diamond drill holes and the following measurements: intact rock strength, structural orientation, RQD, and joint condition and spacing (Golder. 2016). Lithologies can be divided into two broad groups. The larger group (LIF, HMO, LMO, UHMO, UIF, QC, HBLD), consists of high RQD (90-100%) rock. The smaller group (Limonite), consists of low RQD (0-25%) rock (Golder. 2016). Areas of modelled low RQD can be used to confirm preliminary dewatering well targets, first identified in the geologic model, and identify supplementary targets.

4 DISCUSSION

Identifying productive dewatering wells is challenging at IOC even with extensive diamond drilling, modelling of the geology, and a comprehensive understanding of the hydrostratigraphy. The stakes are high, as drilling and constructing dewatering wells is a time consuming and expensive endeavor. A dry well represents millions of dollars of lost investment and even higher additional future costs due to the absence of effective advanced dewatering infrastructure. For the cost of a diamond drill hole, which regardless of the intended outcome has inherent geological, geotechnical, and hydrogeological value, the risk to the business can be mitigated. This discussion will examine how diamond drilling was successfully applied, in Luce Pit, to identify the strategically situated, long lived, and productive In-Pit 15 (IP15) dewatering well.

IP15 was completed as part of the 2015-2016 dewatering well program. At the time there was a need for significant dewatering support in the central and southern portions of the 2,500 m long pit. Of the then 11 operational wells (Ex-Pit 1, Ex-Pit 2, Ex-Pit 3, Ex-Pit 4, IP1, IP2, IP3, IP7, IP8, IP9, and IP10) 70% targeted the West Wall Shear Zone (WWSZ) and were confined to the north-west end of the pit. The remaining 30% of the wells targeted several different geologic structures, including the prominent NW Main shear zone, all concentrated at the south end of the pit. Spatially, this resulted in most of the wells existing in a narrow band, parallel to D2 strike, along the west wall of the pit (Figure 4).

The NW Main shear zone was chosen as the target for IP15 in a deliberate attempt to diversify dewatering activity away from the WWSZ. The NW Main structure

was intriguing because it represented a different generation of deformation and was also the furthest easterly (potentially) viable well target in Luce Pit at that time. This shear zone, located in the south-east corner of the pit (Figure 4), is clearly visible in the wall as brecciated and limonitic rock juxtaposed against pristine crystalline iron formation (Figure 5). It is up to 60m wide, has a steep 75-80° dip at surface, and appeared in several nearby diamond drill holes indicating that the structure likely continued to depth.

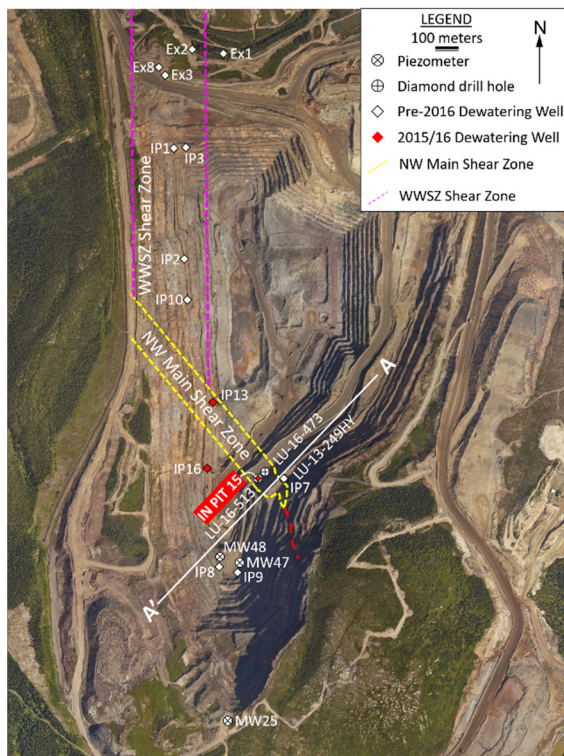


Figure 4. Plan view map of Luce Pit (this map is oriented to mine north). Note, location of A'-A cross section. Cross section is depicted in Figure 6b.

Determining the precise location and depth of all well targets, IP15 included, begins with a review of available information including the geologic and geotechnical RQD models, the diamond drill hole database, and the diamond drill core photo library. In the case of selecting the locations of the sister wells to IP15 (IP13 and IP16) the models were almost exclusively used. In both instances the geologic and geotechnical models predicted significant volumes of hydrogeologically favorable rock at depth. With volumes that substantial, based off many existing diamond drill holes, there was high confidence in these production wells being successful water producers. In both cases, it was decided that drilling diamond drill holes was not necessary. However, targets were examined with two 6 ¼ inch diameter pilot wells on which airlift tests were completed, and chip samples logged, both of which confirmed the viability of the well targets. IP13 and IP16, each capable of sustainably producing 1,200 to 1,400

gallons per minute, are two of the most productive wells ever drilled at IOC.

IP15, like IP13 and IP16, was initially identified through the geologic and geotechnical models (in conjunction with field observation) and proved a more onerous target in several ways. From a mine design perspective, the only area unchanging in the long-term that also aligned vertically with the NW Main shear zone was a narrow bench between the pit face and the main haul road to the bottom of Luce Pit (Figure 6a). Geology proved to be an even bigger challenge. The narrow width and steep dip of the NW Main shear zone (6b) in combination with its sharp contacts with surrounding crystalline non-porous hanging wall and foot wall rock, confirmed to depth in nearby ddh LU-13-249HY (Figure 7a), meant there was little room for error.

A steeply dipping target, sandwiched between crystalline non-porous rock, is a double edged sword. Collaring the well in the right location, drilling down dip almost entirely in porous and permeable rock, would result in a productive well. Collaring the well in the wrong location, too far to either edge of the fault by only tens of meters, would result in a non-productive well drilled entirely in unfavorable rock. Collaring somewhere in between would result in a second-rate well. The potential for an undesirable outcome was deemed too high, even with existing diamond drill hole and model data, and the decision was made to diamond drill before moving forward with a well.

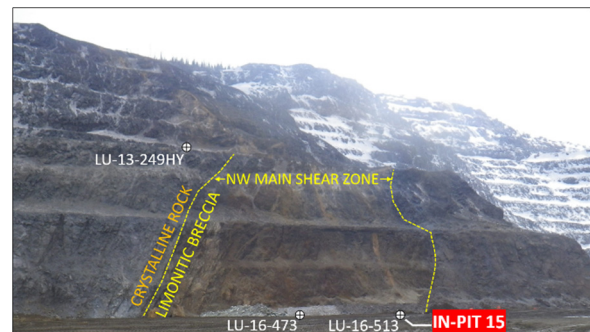


Figure 5. NW Main shear zone. View looking south.

In April 2016 diamond drill hole LU-16-473 (Figure 6b & 7b) was drilled vertically, to a total depth of 172 meters of a planned 200 meters, at the preferred IP15 target location. The collar was located in the middle of the NW Main fault (Figure 5). The drill hole was terminated before it reached planned depth due to drilling out of the NW Main shear zone and into solid crystalline rock at a disappointing 70 meters deep. The shallow depth of the limonitic intersect did not justify a well at this location.

The NW Main shear zone, in spite of the disappointing LU-16-473 results, was still believed to be a viable target. The model was reviewed, the geologists consulted, and a decision made to shift the IP15 target 34 meters south-west and drill a second diamond drill hole.

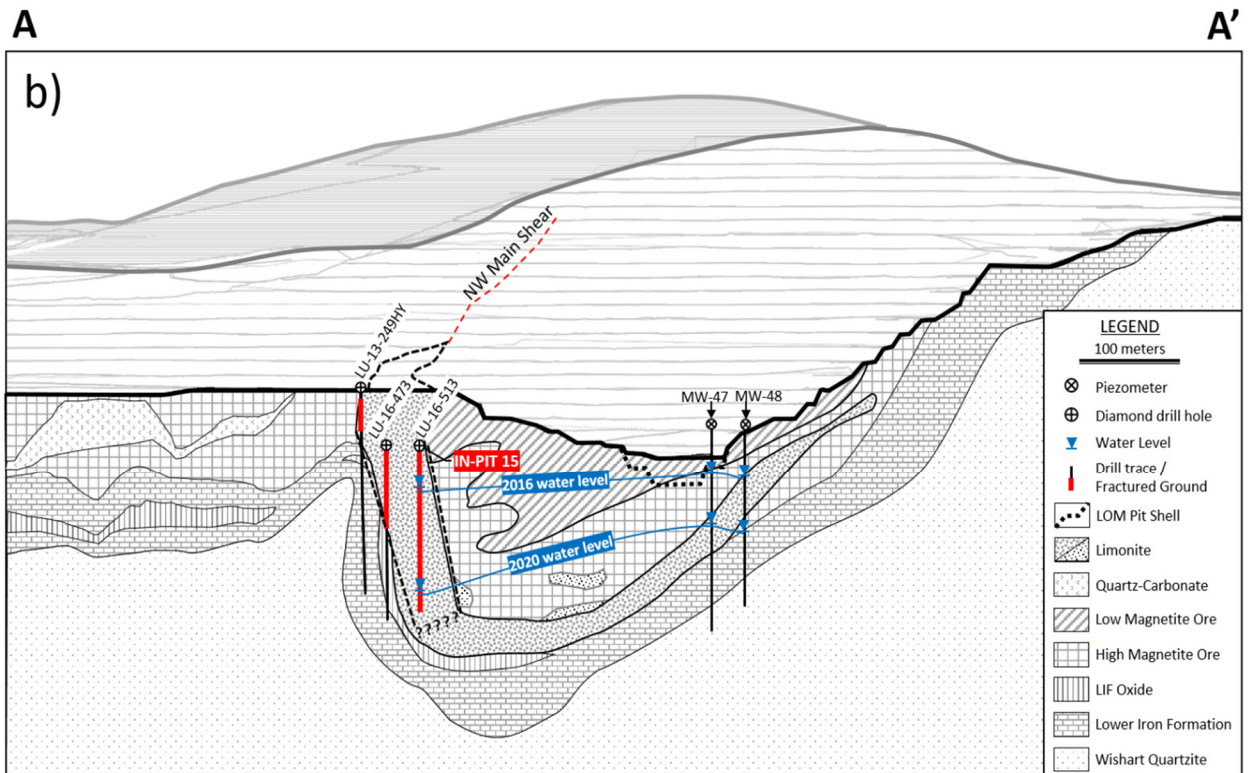
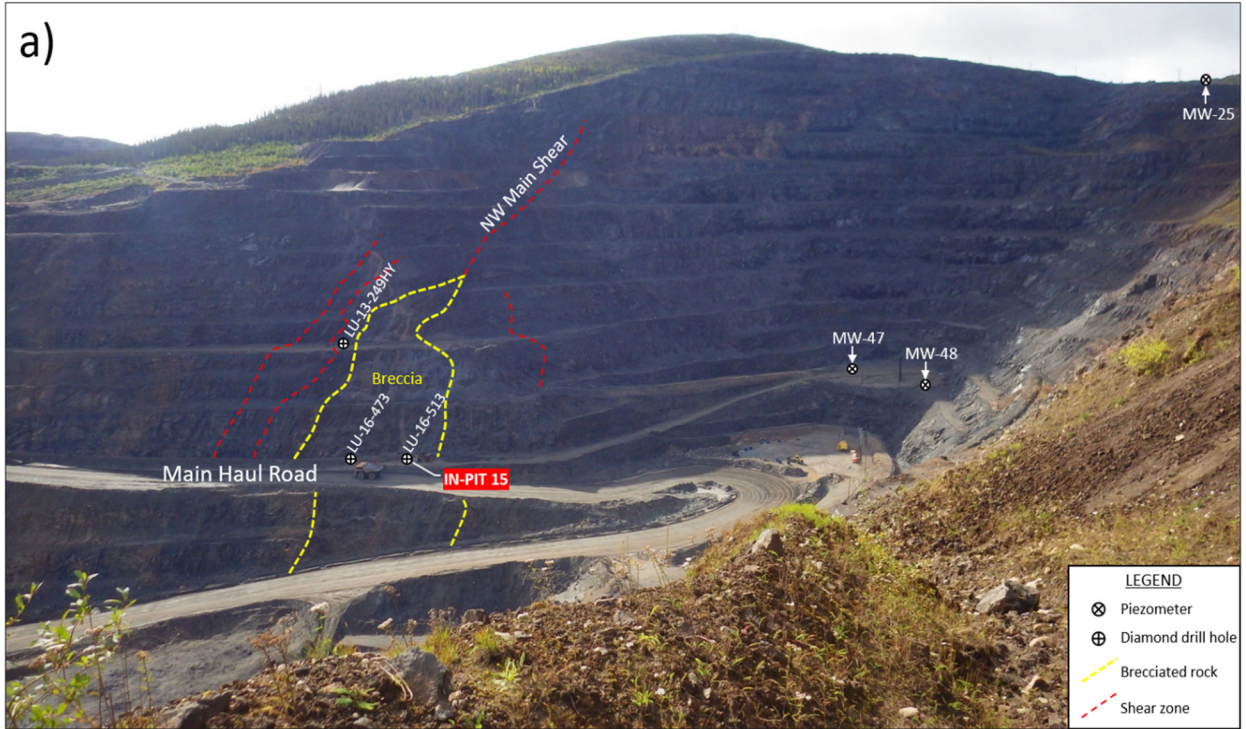


Figure 6. a) Photograph of the south end of Luce Pit, view looking south, annotated with the outline of the NW Main shear zone based on SRK's 2018 interpretation. Note the location of diamond drill holes, In-Pit 15, and the main haul road. b) Annotated geologic cross section, paralleling the photo, of the south end of Luce Pit. View looking south. Note the location of the NW Main shear zone, In-Pit 15, and the location of diamond drill holes and monitoring wells. Red denotes hydrogeologically favorable (limonitic, low RQD) ground.

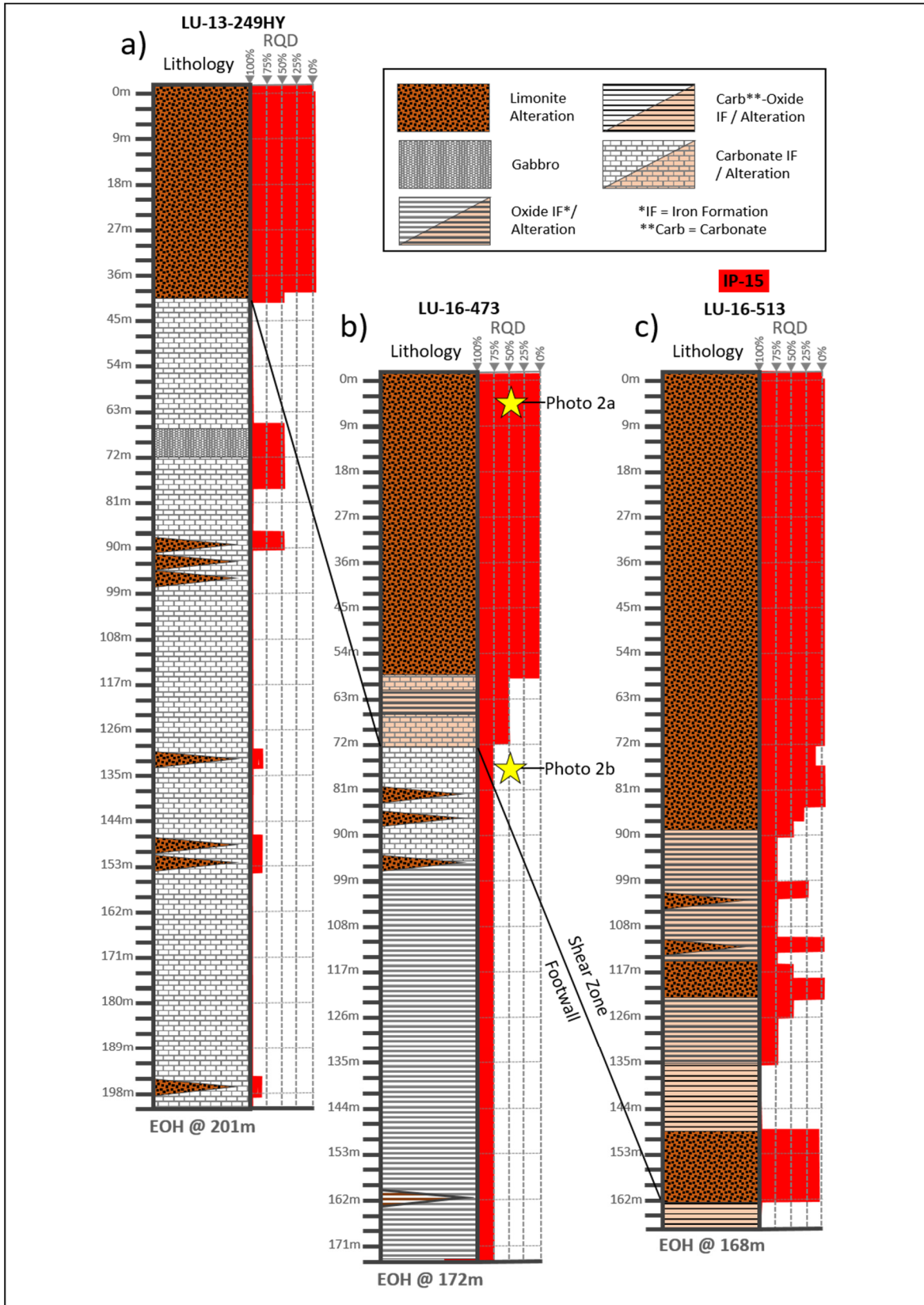


Figure 7. a) LU-13-249HY stratigraphic log. b) LU-16-473 stratigraphic log. Note location of Figure 2 photos. c) LU-16-513 stratigraphic log. Note, that this is the diamond drill hole that was developed into IP15.

In July 2016 ddh LU-16-513 (Figure 6a & 7c) was drilled, vertically, to a total depth of 167 meters of a planned 200 meters. The collar was located at the south-west edge of the NW Main fault. The hole was stopped short due to difficult drilling conditions (soft and blocky ground). Core results showed that almost the entire length the hole was in hydrogeologically favorable ground. In this instance, even though the hole ended before reaching planned depth, the deep and continuous depth of the limonitic intersect justified the construction of a well. Subsequently, to confirm viability, a 6 ¼ inch pilot well (MW95) was drilled to 205 meters directly over the diamond drill hole trace. The pilot well confirmed the presence of water and limonite, a proxy for porosity and permeability, in various concentrations to 205 meters; in addition to suggesting favorable yields from airlift testing.

5 CONCLUSIONS

IP15 was completed as a 22" diameter well with a 16" steel cased completion, almost entirely within hydrogeologically favorable rock, to 208 meters depth. It was commissioned during September 2016 and continues to operate at the time of publication. Upon activation, the initial pumping rate was 1,200 gpm and the sustained pumping rate during the first year of operation was >1,000gpm. Since activation, together with IP13 and IP16, it has dropped the water level in the south end of Luce Pit by roughly 100 meters. These wells bolstered the operation and opened up a previously saturated zone of rich ore more than paying back the cost of constructing and operating the wells themselves. This makes IP15 one of the most effective wells ever drilled at IOC and definitely the most productive well ever constructed in the hydrogeologically favorable but geologically complex NW main shear zone. A positive outcome, even with computer models and nearby diamond drill holes, was not guaranteed. Success is attributed in large part to first confirming a viable, limonitic low-RQD, target via diamond drilling.

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