

Groundwater Occurrence at, and Advanced Dewatering of, a Geologically Complex Orebody at the Iron Ore Company of Canada Open Pit Mine in Subarctic Labrador Canada



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ABSTRACT

Located in Western Labrador, the Iron Ore Company of Canada (IOC) has operated the Carol Lake Mine since the official opening in 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 mine is located in the Sokoman Iron Formation within the Labrador Trough. The orebody has been strongly metamorphosed, deformed, and subjected to variable supergene (limonitic) alteration resulting in a complex hydrogeologic setting. A broad knowledge of the hydrogeology exists and many successful dewatering wells have been constructed to good effect. Successful and efficient mining, below water table, is dependent upon these wells dewatering the orebody early, before mining starts, and sustainably pumping for the long-term.

RÉSUMÉ

Située dans l'ouest du Labrador, la Compagnie Minière IOC exploite depuis 1962 la mine à ciel ouvert de Carol Lake. Rio Tinto, Mitsubishi et Labrador Iron Ore Royalty Corporation sont les actionnaires de la compagnie Minière IOC qui produit du concentré de fer ainsi que des boulettes pour la vente à l'international. Géologiquement, la mine est localisée dans la formation de Sokoman de la « fosse du Labrador ». Le gisement a été fortement métamorphosé, déformé et assujéti à des altérations supergènes d'intensité variable (limonitique) entraînant la création d'un réseau hydrogéologique complexe. Nous avons une bonne compréhension de ce système et de nombreux puits de pompages ont été construits avec un résultat satisfaisant. Le succès des activités d'extraction minières est directement dépendant du bon fonctionnement de ces puits pour dénoyer le gisement durant toute la durée de l'exploitation.

1 INTRODUCTION

In 1962 the Iron Ore Company of Canada (IOC) opened the Carol Lake Mine and associated beneficiation facilities (concentrator and later pellet plant) in western Labrador (Figure 1). Prior to that, during the 1950s, the company was mining DSO (direct shipping ore) from orebodies straddling the boundary between Labrador and Quebec near Schefferville.

IOC has three shareholders: Rio Tinto (site manager), Labrador Iron Ore Royalty Company, and Mitsubishi Corporation. The combined operation (mine, beneficiation, rail, and port) employs over 2,400 people in Labrador City, Sept-Iles, and Montreal. There are currently five operational pits (Luce, Moss, Humphrey Main, Humphrey South, and Lorraine). 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). Saleable product is transported to IOC's Sept Iles port facility by its wholly owned QSNL railway.

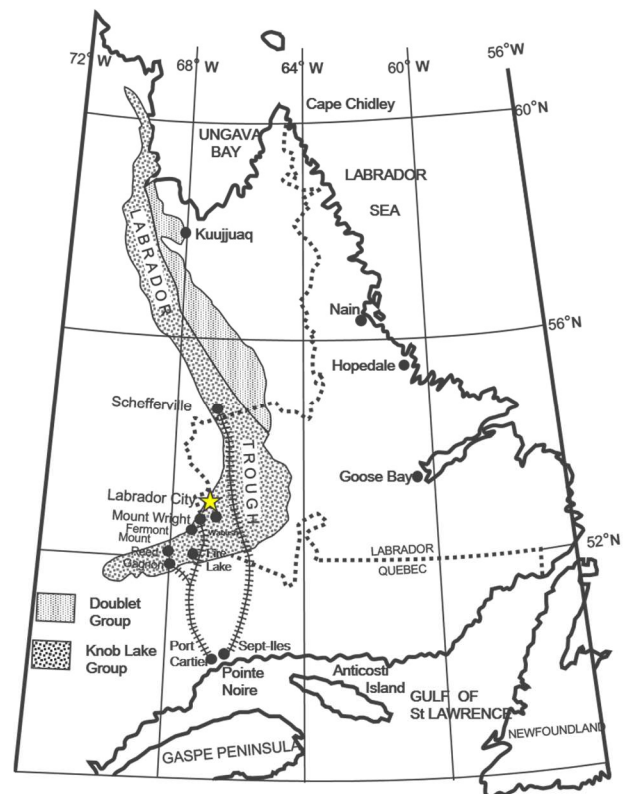


Figure 1. Geographic map of Labrador showing the location of the mine relative to the Labrador Trough. Modified after Rivers and Wardle (1978).

2 GEOGRAPHY AND CLIMATE

2.1 Location

Carol Lake mine is situated in an established mining district in the western uplands of Labrador at an elevation of 785 to 845 meters above sea level (MASL). The mine is located roughly 10km north of Labrador City in the province of Newfoundland and Labrador. Ecologically, the area is classified as a Mid-Subarctic forest ecoregion (Roberts et al. 2006).

The topography of the area is characterized by rugged rolling hills and valleys shaped during the last ice age and controlled by the bedrock geology (SEM Ltd. 2018).

Neighboring mines include Scully (Tacora), Lac Bloom (Quebec Iron Ore), and Mt. Wright (Arcelor Mittal).

2.2 Climate

The region experiences long cold winters and brief cool summers placing it in a continental subarctic climate zone (SEM Ltd. 2018). Climate data is regularly collected at Wabush Lake Airport (climate ID 8504175) (located 8km southeast of the mine). Historic data, collected at Wabush Airport, has been summarized in Table 1.

Table 1. Average temperature and precipitation 1981-2010.

	Rainfall (mm)	Snow (cm)	Precip (mm)	Avg Temp (°C)
January	0.6	63.8	49.2	-22.2
February	1.6	50.9	40.3	-20.6
March	2.6	65.9	54.1	-13.3
April	12.1	44.3	48.8	-4.3
May	40.4	14.4	53.5	4
June	80.6	2.1	82.7	10.3
July	113.9	0	113.9	13.8
August	103.4	0.1	103.5	12.5
September	92.3	4.4	96.5	7.6
October	42	39	75.7	0.5
November	10.9	77.5	70.9	-8.2
December	2.5	66.2	50.4	-17.5
Year	502.9	428.7	839.5	-3.1

Overall, the average yearly temperature is -3.1°C. Daily average temperatures range from a high of 13.8 in July to a low of -22.2°C in January. Average monthly temperatures are positive from May to October and negative from November to April.

Winter monthly average snowfall ranges from 44.3 to 77.5cm and spring through fall monthly average rainfall

ranges from 53.5 to 113.9mm. The site receives nearly half its precipitation during the summer (June through September) (SEM Ltd. 2018).

It is important to note that there are two seasonal events which strongly influence site groundwater levels: the spring thaw, or freshet, and the winter freeze-up. They are elaborated upon in Section 3.2.4 (Hydrogeology).

3 GEOLOGIC SETTING

3.1 Regional Geology

3.1.1 Labrador Trough

The Labrador Trough is approximately 1,000km long, Proterozoic aged, sequence of predominantly clastic and chemical sedimentary rocks (Neal. 2000) (Figure 2). Oriented roughly north south it underlies western Labrador and portions of Quebec (SRK Ltd. 2018). The Carol Lake project is located in the mid-southern portion of the trough.

This sedimentary sequence was originally deposited on a continental margin (Conliffe. 2012) on top of the much older rocks of the Ashuanapi Metamorphic Complex (part of the Superior Craton). Deposition occurred between 2.17 and 1.87Ga ago (Wardle et al. 2002).

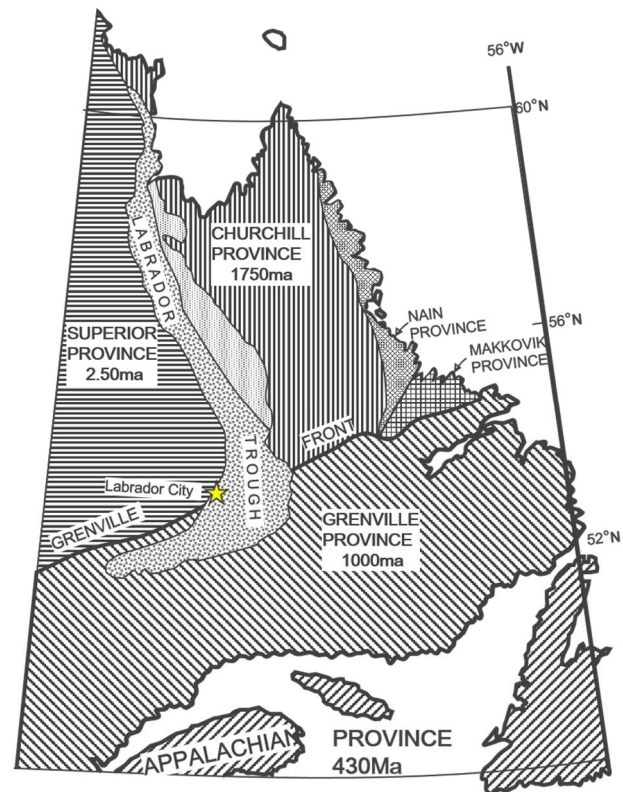


Figure 2. Map showing geologic provinces with their approximate radiometric ages (Ma = millions of years). Modified after Rivers and Wardle (1978).

Protoliths of relevant regional geologic units, listed from oldest to youngest, are: shales (Attikamagen Formation), carbonates (Denault Formation), iron formation (Sokoman Formation), deep water turbidites (Menihék Formation) (Coates. 2012).

3.1.2 Sokoman Iron Formation

In the vicinity of the Carol Lake mine the Sokoman Formation conformably overlies the Wishart or Attikamagen Formations (Coates. 2012). The Sokoman Formation, ranging between 30 to 170m in thickness (Neal. 2000), is one of the largest continuous iron formations in the world (Coates. 2012). It is classified as Lake Superior Type, due to its extent and depositional environment, and contains impressive 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 Formation. The three units that compose the formation have been creatively named (at IOC): the Upper Unit (UIF), the Middle Unit (MIF), and the Lower Unit (LIF) (Figure 3). 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.

Formation		Primary Rock Types
Shabagamo		Metagabbro gneiss dykes and sills with lesser amphibolite schist
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.
Attikamagen		The oldest formation of the Knob Lake Group comprising medium to coarse-grained quartz-feldspar-biotite-muscovite schist and lesser gneiss.

Figure 3. Stratigraphic column showing the Sokoman Formation.

3.2.2 Structural and Metamorphic Geology

The Sokoman, in the vicinity of Carol Lake, has been subjected to folding, faulting, and metamorphism from at least two mountain building events (the Hudsonian orogeny at ~1,500 Ma and the Grenvillian orogeny at

~1,000 Ma) (Coates. 2012). As a result of the complex tectonic and metamorphic history the rocks are characterized by thrust faults, non-cylindrical folding, and medium to high metamorphic grade (Rivers and Wardle. 1978).

3.2.3 Supergene Alteration

In general, at IOC, limonite alteration (Figure 4) is associated with fault zones (propagating down dip to depths >200m) and is strongest closest to surface (in places almost a regolith) with alteration intensity decreasing with depth. Kaolinite clay seams are found within the limonite zones.

Limonite is a general term for a mixture of iron oxyhydroxides (e.g. $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ and goethite $[\text{FeO}(\text{OH})]$) with variable physical and chemical properties (massive, earthy, yellow/orange/brown appearance)

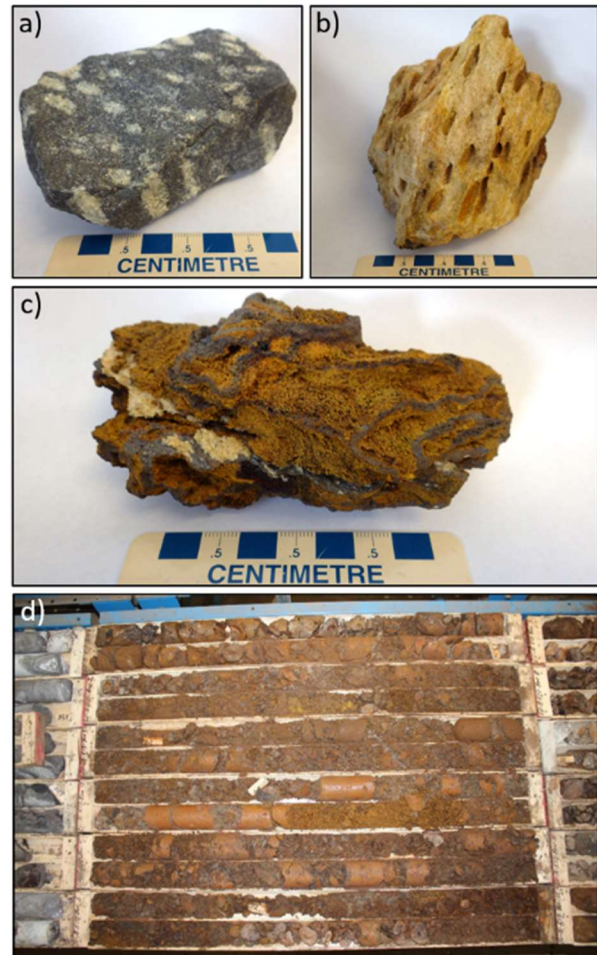


Figure 4. a) Un-weathered iron formation containing distinct carbonate-rich lenses. b) Weathered quartz-carbonate rock. Note, distinct lens shaped vugs which contained minerals prior to weathering c) Limonite-rich rock. d) Limonite altered rock from drill core (LU-16-513) retrieved from IP15 location before drilling well. Hole collared 162m below pit crest. Photo location shown on Figure 7 map.

formed from the oxidation (weathering) of iron bearing minerals (Neuendorf et al. 2005). Other weathering indicators occurring at IOC are silicate mineral dissolution and kaolinite seams.

Supergene weathering, which survived the glaciation of the past ~1.8 million years, has been proposed as the source of apparent deep weathering characteristics (limonite, kaolinite seams, and silica dissolution) observed in nearby ore deposits (e.g. Julienne Lake) (Coates. 2012).

Deep weathering is most commonly the result of warm tropical climates. Evidence of this type of climate was identified ~200km north of Carol Lake at Redmond No 1 deposit near Schefferville. During the summer of 1958 Dr. Erling Dorf (Princeton University) collected fossils of 36 species of plants and insects: 27 angiosperms, 4 ferns, 3 conifers, 1 lycopod, and a new genus and species of termite (Dorf. 1959). Based on these fossils Dorf postulated that these rocks were deposited, during the Early or Early Late Cretaceous, in a shallow lacustrine basin which experienced a warm and humid climate.

3.2.4 Hydrogeology

The weathered/limonitic rock masses, with conductivity values in the range of 10^{-7} to 10^{-4} m/s (Piteau Associates. 1981) are the most significant hydrostratigraphic units at Carol Lake. Piteau Associates (1981) speculated, while mining was taking place at relatively high elevations, that IOC's pits did not intercept regional scale groundwater flows. However, as mining has progressed significantly deeper this is less likely to be entirely the case presently.

As stated earlier, in section 2.2, there are two seasonal events which strongly influence site groundwater levels: the spring thaw and the winter freeze-up. Spring thaw, or freshet, begins in mid-April with the melting of snow and ice and lasts for several weeks until the snowpack has completely thawed. During this time, within a week to two weeks of the start of runoff, groundwater elevations rebound from their lowest to their highest levels with an almost mathematical precision (Figure 5). The opposite trend happens during winter freeze-up which has a more

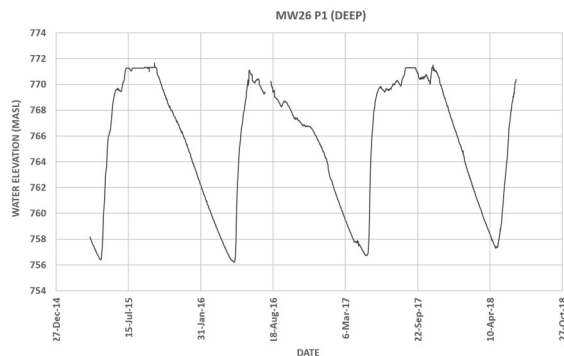


Figure 5. Three year groundwater elevation at representative piezometer MW-26. See location on Figure 7 map. Note, flat sections of curve represent water overflowing the piezo casing.

variable start date ranging from the end of September to the end of October and lasts all winter. During this time the water level gradually falls.

4 DISCUSSION

Of all the operating pits at Carol Lake, Luce Pit (Figure 6) with its long production history, future production requirements, and complex geology best exemplifies the dynamism of hydrogeologic issues at IOC and as such will be the focus of this discussion.

Currently Luce is the largest operating pit at IOC measuring roughly 2,500m long by 1,300m wide and 170m deep. Development began in the late 1990s and, for the past two decades, has been a major ore source for the operation. Mining activity reached the water table over a decade ago and during this time sumps were used, with great difficulty and minimal effectiveness, to dewater the pit (T. Leriche personal communication).

Presently the pit is halfway to final depth. It is clear that successfully, safely, and profitably mining below water table requires advanced dewatering achieved through the installation of deep dewatering wells. At Luce there are currently eight operating wells situated within the pit or near the pit perimeter: IP-12, IP-13, IP-15, IP-16, IP-18, Ex-Pit 1, Ex-Pit 2, and Ex-Pit-3 (IP = In Pit). These wells dewater the pit and assist with reducing the pore-pressure behind in the pit walls. In addition two deep wells (DW20 and DW21), yet to be commissioned, were constructed during 2019 in the bottommost portion of the pit to support mining to even deeper depths.

Dewatering wells are constrained to areas of the pit that will not be mined out, in the near to medium term, and which also align vertically with favorable hydrostratigraphic zones. So valuable are productive wells, when no other option exists, the planning engineers have reconfigured pit slopes and mining sequences to allow for the construction or preservation of well infrastructure.

This three way alignment of hydrogeology, pit design, and well construction is depicted in the attached map of Luce Pit (Figure 7). The Luce orebody itself is a series of plunging, tight, asymmetric synforms and antiforms which are cut by younger faults (Figure 8). Multiple significant brittle faults are present along the west wall. These faults strike roughly north-south and dip to the east and extend to an undetermined depth under the pit. The rock that they cut across has undergone limonitic alteration as the result of supergene weathering, guided to depth by the faults, which has increased the porosity and hydrogeologic connectivity of the rock mass to the point that it acts like a sponge. Wells targeting this zone, along the west wall, are IP12, IP13, IP16, IP18, DW20, and DW21 (DW = Dewatering Well) as well as seven wells which were successfully dewatered and therefore reached the end of their useful lives. In the south end of the pit there is another brittle fault, more narrow and at a different orientation (striking northwest and dipping southwest), but also with a limonite alteration



Figure 6. Luce Pit (June 2017). Photograph taken from north end of the pit. View looking south.

overprint. Drilling a successful well in this fault proved challenging due to its narrow width and steep dip. Two wells were drilled, on different benches, at this location one of which was productive (IP15).

In Luce, the impact of the pumping from dewatering wells on the local water table is observed through a network of roughly thirty-five instrumented and non-instrumented vertical standpipe nested piezometers. Solinst brand equipment (M30 to M200 level probes and direct read cables), recording water level readings every two hours, are currently used. Data integrity is maintained via a weekly manual dip schedule. An additional twenty angled nested vibrating wire piezometers (VWP), manufactured by RST and maintained by the IOC Geotechnical Department, augment the standpipe network. Every year the monitoring network is expanded for two primary, complimentary purposes: 1) identifying deep dewatering well targets and 2) expanding the understanding of the groundwater table before, during, and after dewatering activity.

Historic water level data, collected from the monitoring well network, indicates that lowering the water table in Luce is a time dependent process. One in which wells must continually operate with minimal downtime for an extended period. This phenomenon can be seen in cross-section B-B' (Figure 9). B-B' is a north-south section, view looking west, running parallel to the limonite altered fault zones along the west wall of Luce Pit. In the south end of the pit, which is the left side of the figure, are IP13, IP15, and IP16.

These wells were activated in 2016 and have more-or-less been consistently pumping ever since. Before these wells were started the water level was roughly one bench (13.7m) below the pit floor. Presently, after three years of pumping, the water level is ~100m below the pit floor in the vicinity of these wells. In the north end of the pit, which is on the right side of the figure, are IP18, DW20, and DW21. Only one of these wells is currently operating (IP18) and that well was activated just over a year ago. DW20 and DW21 were drilled in early 2019 and are currently being equipped with pumps. One year ago, in the vicinity of these wells, the water level was at the pit floor. Presently the water level is roughly one bench below the pit floor.

The time dependency of dewatering can be seen again in cross-section A-A' (Figure 8). A-A' is an east-west section, view looking north, and running perpendicular to the limonite altered fault zone. In the west side of the pit, which is on the left side of the figure, can be seen the approximate extent of the limonite zone, the faults extending to depth, and the water table roughly one bench below the current pit floor. Looking to the center and east of the pit, the center and right in the figure, the water levels remain high at or just below the current pit floor. The rock in this area of the pit is non-porous, slow draining, and hydrogeologically fracture dominated.

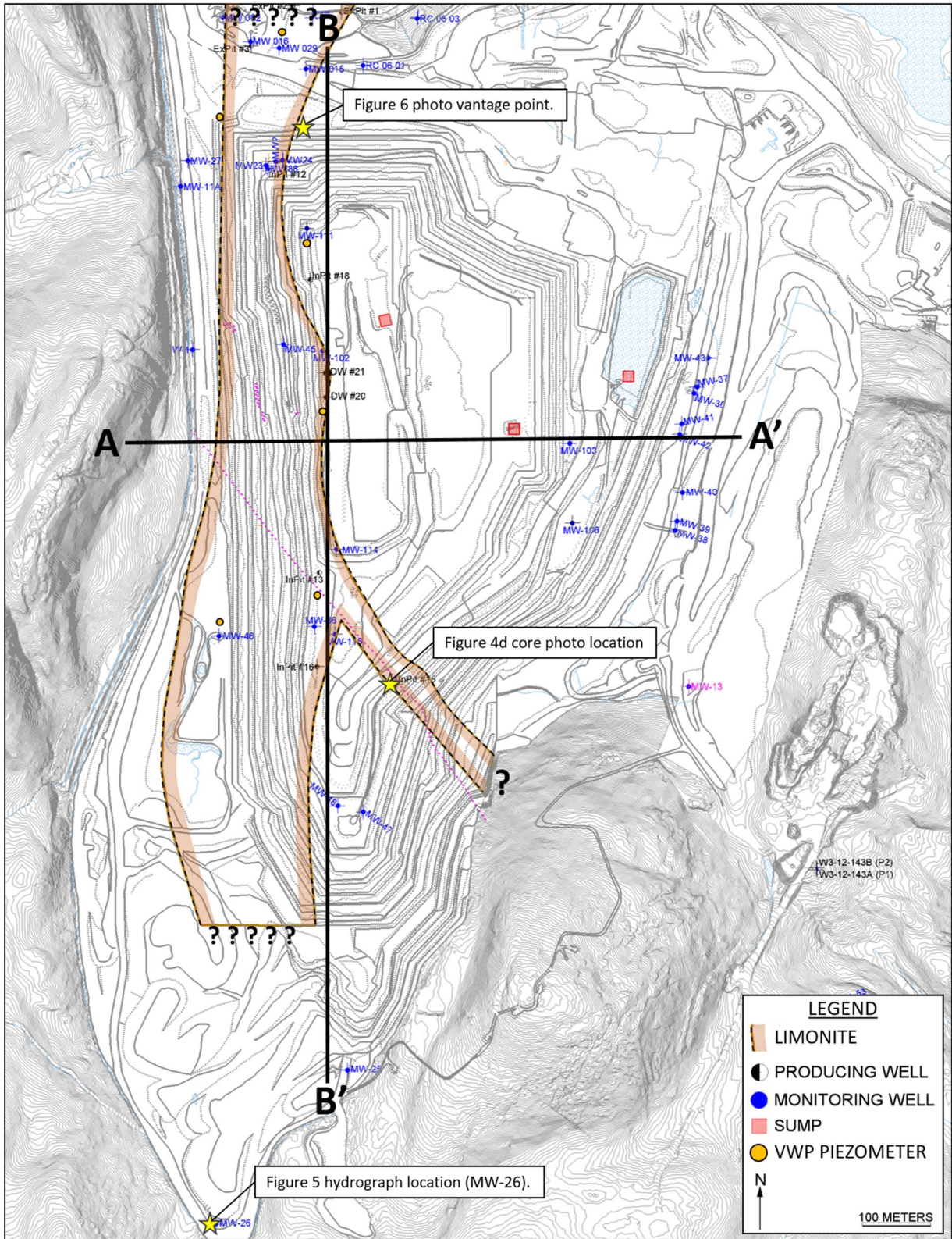


Figure 7. Plan view map of Luce Pit (this map is oriented to *mine north*). Note location of Figure 4d core photograph and location of Figure 5 hydrograph (MW-26)

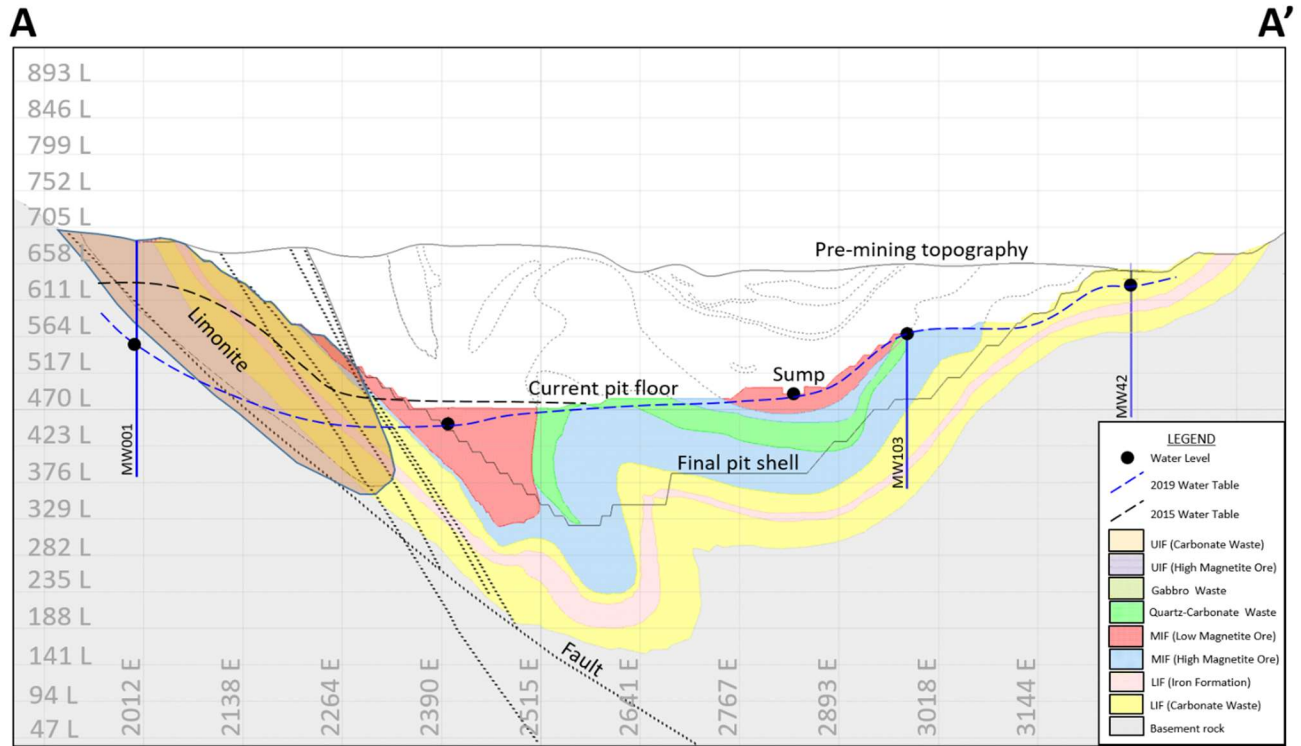


Figure 8. Cross-section A-A'. View looking north. Well MW-01 projected onto this section from ~100m further north.

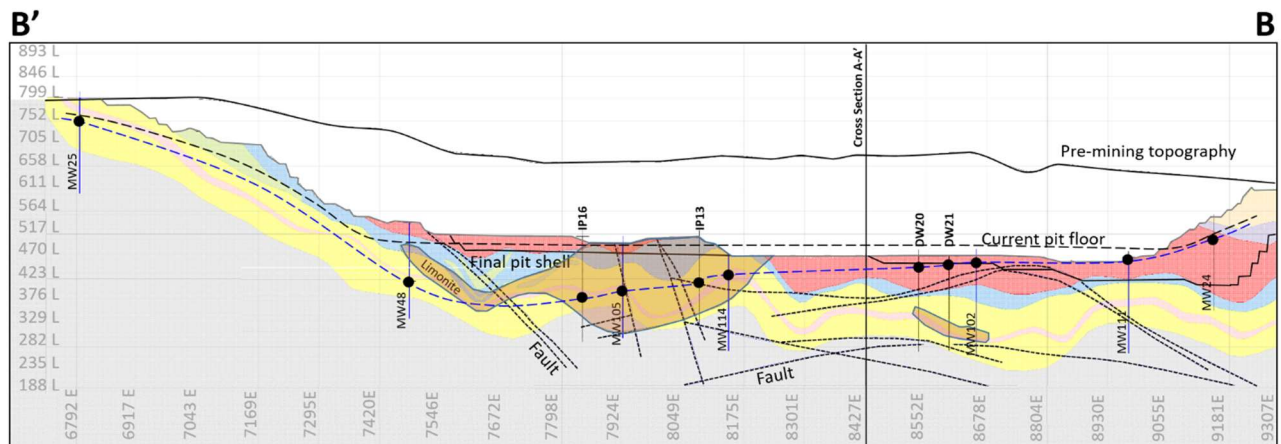


Figure 9. Cross-section B-B'. View looking west. MW-24 projected onto this section from ~50m to the west. Orebody dipping toward viewer making the ore zone appear thin. Note location where section A-A' intersects.

5. CONCLUSIONS

At IOC, like a majority of mines, successful mining is heavily dependent upon early dewatering of the orebody (in advance of mining) and reliable sustained long-term pumping after mining begins.

Before mining starts a significant amount of work is completed by a multidisciplinary team of geologists, geotechnical engineers, mining engineers, and hydrogeologists. Diamond drilling and mapping of the orebody occurs and is followed by identifying and interpreting the lithologies, structures, and alteration. The hydrogeologists build upon and expand this understanding of the orebody in the pursuit of optimal dewatering well targets, complimentary to the pit design, to support mining.

In the case of IOC, at the highest level the hydrostratigraphy of the orebody can be broadly divided into two hydrogeologic domains. Domain 1 is the largest by every measure and consists of un-weathered iron formation and associated rocks. Rock within this domain is non-porous and the hydrogeology dominated by complex fracture networks. Domain 2 consists of zones of weathered limonitic rock propagated to depth along faults. Rock within this domain is porous, permeable, and internally well connected with high k values. At IOC the Hydrogeology Department has utilized this basic understanding to identify and drill deep dewatering wells with great success.

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