MADRID-BOSTON PROJECT
FINAL ENVIRONMENTAL IMPACT STATEMENT

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Glossary and Abbreviations

Terminology used in this document is defined where it is first used. The following list will assist readers who may choose to review only portions of the document.

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
CCME	Canadian Council of Ministers of the Environment
HBVB	Hope Bay Volcanic Belt
K	Hydraulic conductivity
m	Metre
mbgs	Metres below ground surface
MMER	Metal Mining Effluent Regulations
QA/QC	Quality assurance and quality control

2. Groundwater

2.1 EXISTING ENVIRONMENT AND BASELINE INFORMATION

2.1.1 Regional Setting

2.1.1.1 Geologic Context

The Hope Bay Volcanic Belt (HBVB) is a greenstone belt that is located in the northeast portion of the Slave Structural Province. The HBVB is mafic volcanic-dominated, typified by massive to pillowed tholeiitic flows interbedded with calc-alkaline felsic volcanic and volcanoclastic rocks, clastic sedimentary rocks, and rarely synvolcanic conglomerate and carbonates.

Multiple Quaternary Ice Ages produced an extensive glaciated landscape that was covered by successive Laurentide ice sheets. The Last Ice Sheet started receding about 8,800 years ago (Dyke and Prest 1986) leaving an extensive blanket of basal till. Immediately following the de-glaciation, the entire Hope Bay region was submerged approximately 200 metres (m) below present mean sea level (Dyke and Dredge 1989). Fine sediment, derived from meltwater (rock flour), was deposited onto the submerged Hope Bay shelf as marine clays and silts onto the basal tills. The greatest thicknesses accumulated in the deeper water zones, now represented by valleys.

Isostatic rebound after the de-glaciation resulted in emergent landforms and reworking of the unconsolidated marine sediments and tills along the prograding shoreface (EBA 1996). Sediments were easily stripped off the uplands and redeposited in valleys, leaving relatively continuous north-northwest trending bedrock ridges and elongate lakes. The unconsolidated overburden, now up to 30 m in thickness, comprises locally and regionally derived tills and boulder tills with lacustrine and marine sediments and clay up to 15 m thick in the larger valleys.

A complete description of bedrock and overburden geology is provided in Volume 4, Section 4.

2.1.1.2 Groundwater Flow

The Project is situated within the zone of continuous permafrost, as delineated in a database compiled by the Geological Survey of Canada (Smith and Burgess 2002). Although it is generally understood that groundwater flow does not occur in permafrost, it can move in features called talik, where rock is unfrozen. A talik is defined as "a layer or body of unfrozen ground occurring in a permafrost area due to local anomalies in thermal, hydrological, hydrogeological or hydrochemical conditions" (van Everdingen 1998). In most cases, taliks are formed by lakes and other waterbodies that cause a local departure in terrestrial ground temperature (Smith and Hwang 1973; Burn 2002). Taliks can be closed or open. A closed talik is an unfrozen zone beneath a water body that is enclosed at the base and the surrounding sides by permafrost; and an open talik is an unfrozen zone beneath a water body that penetrates the permafrost completely and may connect suprapermafrost (i.e., the layer of ground above permafrost) and sub-permafrost (i.e., the non-frozen ground below the permafrost) groundwater.

Key factors influencing talik configuration include water bottom temperature, lake size (half-width or radius), present and past ground thermal regime, and long-term changes to the landscape. Taliks are transient features. Present-day water bathymetry can affect talik configuration where shallow water allows for ice to seasonally freeze to the bottom (bottom-fast ice) and conduct heat from the ground (Burn 2002; 2005; Stevens et al. 2010a, 2010b). The long-term thermal and physical evolution of the landscape is a factor in the present-day configuration of taliks that extend hundreds of metres below ground surface (mbgs). Lunardini (1995) showed temperature at depths up to 600 mbgs can be influenced by surface temperatures as far back as 100,000 years.

Two groundwater flow regimes are present in the context of continuous permafrost environment. A shallow local flow system associated with the active layer, and a deep regional flow system associated with open taliks and sub-permafrost. The groundwater in the active layer is only fluid during the summer months, in the portion that has thawed, bounded below by frozen sediments or bedrock. In the active layer, groundwater is expected to flow following surface topography and discharge to the surface water drainage network. The deep regional flow system is considered as a low flux, lake-dominated flow system, primarily controlled by the presence of unfrozen zones in open-talik beneath large lakes. Away from lakes, the permafrost is widespread, deep, and considered to be essentially impermeable. In the deep system, groundwater is expected to flow according to spatial distribution of levels in lakes supporting open taliks, recharging from high level lakes and discharging to low level lakes.

The potential for a connection between the shallow groundwater system in the overburden units and the deeper bedrock groundwater system will be localized in areas of taliks associated with lakes. Onshore, permafrost exists at relatively shallow depths and keeps the two systems separated. The infiltration of water from the lakes to the deeper groundwater system will be affected by hydraulic properties of sediments found on the lake bottom. Finer-grained materials (e.g., clay) will have a lower hydraulic conductivity than coarse grained materials (e.g., sand), and thus allow less infiltration. The percentage of clay in these lake bottom sediments will have a significant effect on hydraulic conductivity.

2.1.1.3 Groundwater Quality

Deep groundwater is connate, meaning old, or emplaced when sediments were originally deposited. This connate water is highly saline and can have elevated concentrations of major ions and metals. A dataset of groundwater TDS concentrations sampled across the Canadian Shield was compiled and plotted against depth (Volume 1, Annex V1-7, Package P5-1, Figure 24). The dataset regroup TDS concentrations published by Frape and Fritz (1987) and public data reported at mine projects (Back River, Lupin, Meadow Bank, Meliadine, Snap Lake, Courageous, Ekati, Gahcho Kué, and Jay). It shows that brackish to hypersaline water is commonly observed in permafrost environments and salinity (TDS) generally increases with depth. Concentrations on the scale of tens of grams per liter have been measured at depths of 500 mbgs, beneath continuous permafrost.

Gascoyne (2003) reported several potential sources of salinity. The potential sources are: 1) rock-water interactions, including reactions with rock matrix minerals and fracture-filling minerals, 2) soluble salts present at grain boundaries and in fluid inclusions, 3) residual saline hydrothermal fluids, and 4) marine fluids (possibly more saline than present) or basinal brines that entered the rock during ancient times, pre-glacial in origin (Gascoyne 2003). Furthermore, In situ cryogenic concentration due to ice and methane hydrate formation may have concentrated the remaining fluids, as noted for the Lupin Mine (Stotler 2009).

2.1.2 Local Setting

2.1.2.1 Data Sources

The hydrogeological understanding for the Project is based on information from geological and structural mapping (F. Varley, pers. comm. 2016) and site specific field investigations completed in 2004, 2008, 2010, and 2011. Maps showing the locations of groundwater related field data are shown for each mine area in Figures 16 to 19 (Volume 1, Annex V1-7, Package P5-4). A summary of the most relevant documents in this regard is described in Appendix Package P5-4 (Water and Load Balance).

2.1.2.2 Permafrost and Talik Extents

Permafrost and talik extents were assessed using thermal data from thermistor strings, groundwater quality data, and geothermal models. The methods and results are documented in Volume 4 Section 6 (Permafrost). The geothermal models assessed where through talik occurred on a regional scale, and predicted the configuration of open taliks on a local scale. The critical lake dimensions required for open talik to exist were assessed using a one-dimensional (1D) steady state analytical model. The detailed configurations of the open taliks adjacent to the Boston, Madrid South and Madrid North underground mining areas were estimated using 2D thermal modeling, then extrapolated to obtain 3D surfaces (Package P5-4).

Based on measured concentrations of dominant parameters, saline water is considered to induce a freezing point depression. Table 2.1-1 summarizes calculated freezing point depression based on the most reliable groundwater quality observed at the Hope Bay Project. These results suggest that deep groundwater freezes at a temperature of -2°C.

Table 2.1-1. Isotherm Depression Estimates Based on Water Samples from 10WBW001

Parameter	Units	10WBW001 – Zone 1 (548 m)	10WBW001 – Zone 6 (246 m)	10WBW001 – Zone 10 (63 m)
Alkalinity	mg/L	2.0	44.2	49.7
Calcium	mg/L	4,960	749	1,010
Magnesium	mg/L	69.5	702	849
Potassium	mg/L	39	117	160
Sodium	mg/L	7,290	4,130	5,400
Chloride	mg/L	1,900	9,130	11,500
Sulphate	mg/L	981	940	1,160
Calculated Salinity	%	3.2	1.6	2.0
Calculated Theoretical Freezing Point	**°C**	**-1.9**	**-0.9**	**-1.2**

Ground temperatures measured with shallow and deep thermistors are presented below:

- At Boston (Package P5-4, Figure 16), deep ground temperature measurements have been collected from three deep inclined wells, which extended beneath Aimaokatalok Lake (08SBD381A, 08SBD382, 10WBW004, and two inland wells (08SBD380 and 97NOD176).
    - At 08SBD382, the -2°C isotherm was up to 115 m from the shoreline of Aimaokatalok Lake, and located at a depth of 224 mbgs. At 08SBD381A and 10WBW004, it was 17 and 42 m from shore and located at a depth between 202 and 209 mbgs. The offshore position of the 2°C isotherm cannot be explained by the present-day lake configuration nor by lateral heat flow from the adjacent land. Therefore, it is postulated that the permafrost beneath Aimaokatalok Lake has been submerged with lake expansion.
    - At 08SBD380 and 97NOD176, the ground temperature has been measured to a maximum depth of 241 and 247 mbgs, respectively. The base of permafrost is not directly intercepted by these wells and the lowermost thermistor nodes indicate relatively cold permafrost temperatures (-5.1°C at 08SBD380 and -5.5°C at 97NOD176).

- At Madrid South and Madrid North (Figures 18 and 19 in Package P5-4), deep ground temperature measurements have been collected from three inclined wells (08PMD669, 08PSD144, and TM00141):
  - Well 08PSD144 is located beneath an island centred within Patch Lake. Ground temperature measurements at this site indicate relatively shallow permafrost beneath the island (base of permafrost 78 mbgs) due to the surrounding heat from the lake.
  - Well 08PMD669 is located within the area of the Madrid North underground mine workings (Package P5-4, Figure 17) and is instrumented to a maximum depth of 474 mbgs. The base of permafrost is 570 mbgs at this location.
  - Well TM00141 is located within the Madrid South underground mine between Wolverine Lake and Patch Lake. The well extends toward Patch Lake. Ground temperature measured from lowermost thermistor node is -2.6°C at 225 mbgs. The projected base of permafrost is 346 mbgs, intercepting the talik at the edge of the Patch Lake.

At the regional scale, open taliks were estimated to occur beneath circular lakes with a diameter greater than 224 m (i.e., lake radius of greater than 112 m). For elongated lakes, the critical lake width is estimated to be greater than 104 m wide (i.e., lake half-width greater than 52 m). In addition to the surface footprint, lakes must be deep enough to avoid freezing to the bottom. This critical depth was estimated based on the mean annual ice thickness. At a depth of less than 1.3 m (i.e., two-thirds of the mean annual ice thickness), ice freezes to the bottom and the permafrost under the lake is sustained. These three criteria were used to identify, on a regional scale, the lakes potentially supporting open taliks. If the bathymetry of a lake was not known, only the diameter and width criteria were used. Figure 27 (Package P5-4) shows a map of the potential through taliks at the Boston and Madrid areas based on the estimated critical lake dimensions.

At the local scale, at the proposed mines, thermal analyses (Package P5-4) concluded that:

- The Boston mine will be encapsulated by permafrost and will not intercept an open talik or sub-permafrost areas;
- The Madrid North mine will intercept unfrozen ground at Suluk and Naartok; Suluk will be mined in the open talik formed by Patch Lake, and Naartok will pierce through the base of permafrost at a depth of about 430 mbgs;
- The Madrid South mine will intercept unfrozen ground at the edge of the open taliks formed by the Wolverine Lake and Patch Lake; and
- In all cases, these results are considered conservative since the -2°C isotherm model fit underestimates the depth of the talik compared to site ground temperatures.

2.1.2.3 Groundwater Levels

Measurements of pore pressure for Boston, Madrid South and Madrid North are compiled in Tables 2.1-2 and 2.1-3. The pressure is expressed as head (in masl), corrected from the average water density of the groundwater and measured in laboratory from the Westbay well groundwater samples. Since the density varied between 1.00 and 1.03 kg/m^3; the degree of accuracy on the head measurements are ±7 m, which corresponds to a variation in density of ±0.015 kg/m^3. The head levels suggest groundwater table is near the lake surface, which supports the interpretation that the groundwater system in open taliks and sub-permafrost is controlled by lake levels.

Table 2.1-2. Lake Level and Pore Pressure Measurements at Boston

ID	Type	Date	Water Level/ Head (masl)
Aimaokatalok Lake	Lake level	-	65.6 masl
Stickleback Lake	Lake level	-	69.6 masl
08SBD380	Pore pressure	Dec 11, 2008	89.4 masl (Bead zone #12)
08SBD381A	Pore pressure	Dec 11, 2008	60.0 masl (Bead zone #12)
08SBD382	Pore pressure	Dec 11, 2008	63.0 masl (Bead zone #12)
10WBW004	Pore pressure	Sep 14, 2011	67.9 masl (Zone #7) 67.8 masl (Zone #6) 67.6 masl (Zone #5) 68.4 masl (Zone #4) 69.2 masl (Zone #3) 70.4 masl (Zone #2) 69.9 masl (Zone #1)

Table 2.1-3. Lake Level and Pore Pressure Measurements at Madrid South and Madrid North

ID	Type	Date	Head
Imniagut Lake	Lake level	-	27.5 masl
Patch Lake	Lake level	-	25.8 masl
Windy Lake	Lake level	-	18.1 masl
Wolverine Lake	Lake level	-	32.1 masl
08PMD669	VWP	Oct 13, 2008	33.3 masl (Bead zone #12)
08PSD144	VWP	Oct 13, 2008	23.1 masl (Bead zone #12)

2.1.2.4 Hydraulic Properties

Hydraulic conductivity (K) values were measured at Boston, Doris, Madrid South and Madrid North. Data are available for the sediments from 28 in-situ tests and two laboratory tests (SRK 2009a), and for fractured rock from 112 tests (SRK 2009b, 2009c, 2009d, 2011, 2014). Hydraulic testing in fractured rock included short duration packer injection tests (Short Duration Tests) at the three sites and one long-term (about 12 hours) constant head injection test (Extended Duration Test) at the Doris Site. Location maps of the tests are shown for each mine area in Figures 16 to 19 (Package P5-4).

At the local scale, bedrock K is fracture-controlled, comprised of a low bulk K background system intersected by distributed, relatively high K fractures and geologic structures. At the scale of the open-talik, the fractured rocks can be considered as a single unit, without distinction between lithologies, characterized by a relatively higher K at shallow depths, gradually decreasing with depth as confining pressure increases. The only visible trend in the dataset is the progressive decrease in K with increasing depth (Package P5-4, Figure 20), which is a reasonable relationship considering that fractures tend to close with depths. There has been no other trend identified. The spatial distribution of K values does not show a particular pattern and there is no strong relationship established between K and lithology (Package P5-4, Figure 21), nor K and the presence of geologic structures (i.e., fractures and faults; Package P5-4, Figure 22). While no structures have been identified to promote high K, the presence of such features cannot be ruled out. Storativity (or specific storage), influences the “drainability” of surficial material. A bedrock storativity of 3×10^{-7} m^{-1} was estimated from the extended duration test performed at the Doris Site.

A differentiation exists between K in the lake bed sediments and the shallow fractured rocks. The unconsolidated overburden, now up to 30 m in thickness, comprises locally and regionally derived tills and boulder tills with lacustrine and marine sediments and clay up to 15 m thick in the larger valleys. The clay beds present at the bottom of the lake are characterized by a low K, as shown in Table 2.1-4. There are no site specific overburden storativity value measurements. A value of 1×10^{4} m^{-1} is assumed based on scientific literature (Singhal and Gupta 2010).

Table 2.1-4. Hydraulic Conductivity of Doris Lake Bed Sediments

Type	Number of Tests	Average Thickness (m)	Hydraulic Conductivity Geometric Mean (m/s)
Soft lake bed sediments	28	17	1 x 10-8
Indurated lake bed sediments	2	3	4 x 10-10

2.1.2.5 Groundwater Quality

Groundwater samples were collected at Doris and Boston from Westbay wells 10WBW001, 10WBW002 and 10WBW004. The samples were analyzed for standard parameters (conductivity, pH, etc.), cations (chloride, sulphate, etc.), total and dissolved metals. In addition, stable isotopes (O and H) were analyzed to provide improved quality assurance and quality control (QA/QC) on well purging and development, as well as to assess potential variation in water source types. 10WBW001 (i.e., Doris) and 10WBW004 (i.e., Boston) indicated comparable chemistry, but the samples collected at 10WBW001 are considered to be the most representative of true formation water with respect to development and purging (SRK 2012, 2014). The samples collected at 10WBW002 are not considered to be representative because the well could not be purged adequately as a result of low K.

The 75th percentile concentration from post-purging samples collected in zones 1, 6 and 10 of Westbay Well 10WBW001 are presented in Table 2.1-5. The sample results suggest that the water encountered during mining, at least initially, will be saline dominated by chloride, and that salinity will likely vary with depth. The groundwater quality results were compared to the following environmental guidelines: Canadian Council of Ministers of the Environment (CCME) water quality guidelines for freshwater, irrigation, livestock, and marine (CCME 2015) and the Metal Mining Effluent Regulations (MMER) limits for deleterious substances (MMER 2015).

The concentrations of calcium, chloride and sodium are high and show a general trend of increasing concentration with depth. Figure 25 (Package P5-4) shows the observed and modeled vertical profile for chloride concentrations. Other constituents can also have relatively high concentrations but do not correlate with depth. When looking at the potential discharge of groundwater to the environment, the constituents of concern are ammonia, boron, cadmium, chloride, fluoride, iron, manganese, molybdenum, mercury, nickel, selenium, sulfate and zinc because concentrations are above the guideline recommendations.

Chloride concentrations and TDS correlates well ($r^2 = 0.97$); therefore, chloride can be used to estimate TDS using the linear relationship: [Chloride] = 0.6 × [TDS], which was estimated using the groundwater quality samples collected at 10WBW001 and 10WBW002. Figure 26 (Package P5-4) plots the observations and the linear regression curve.

Table 2.1-5. Groundwater Quality (10WBW001) under Doris Lake

Parameters		Units	75th Percentile [n= 19 to 29 (1)]	MMER and CCME Guidelines
Field Parameters	pH	pH units	7.73	6.0 - 9.5 [a1, a2]
	Electrical Conductivity (EC)	µS/cm	52,650	na
	Dissolved Oxygen (DO)	mg/L	11.37	na
	Salinity	%	31.86	na
	Oxidation-Reduction Potential (ORP)	mV	20.5	na
Lab Physical Parameters	EC	µS/cm	48,500	na
	Density	kg/m^3	1.03	na
	pH	pH units	7.63	6.0 - 9.5 [a1, a2]
	Total Dissolved Solids (gravimetric)	mg/L	40,800	3,000 [e]
Anions and Nutrients	Alkalinity, Total (as $CaCO_3$)	mg/L	93.7	na
	Ammonia as N	mg/L	3.5	1.04-15.3 [b2,F]
	Chloride (Cl)	mg/L	19,000	640 [b1], 120 [b2], 110 [d]
	Sulfate (SO_4)	mg/L	2,000	1,000 [e]
Dissolved Metals	Aluminum (Al)	mg/L	0.005	0.1 [b2], 5 [d,e]
	Arsenic (As)	mg/L	0.0025	0.5 [a1], 1 [a2], 0.005 [b2], 0.0125 [c2], 0.1 [d]
	Boron (B)	mg/L	3.24	29 [a1], 1.5 [a2], 0.5 [d]
	Cadmium (Cd)	mg/L	0.00012	0.0086-0.0124 [b1,A], 0.0020-0.0027 [b2,A], 0.0051 [c2], 0.0051 [d], 0.080 [e]
	Calcium (Ca)	mg/L	2050	na
	Chromium (Cr)	mg/L	0.0005	0.001 to 0.0089 [B]
	Cobalt (Co)	mg/L	0.00019	0.05 [d], 1 [e]
	Copper (Cu)	mg/L	0.00064	0.3 [a1], 0.6 [a2], 0.002 [b2,C], 0.2-1.0 [d], 0.5-1.0 [e]
	Iron (Fe)	mg/L	4.81	0.3 [b2], 5 [d]
	Fluoride (F)	mg/L	0.75	0.12 [b2], 1 [d]
	Lead (Pb)	mg/L	0.0003	0.2 [a1], 0.4 [a2], 0.001-0.0018 [b2,D], 0.2 [d], 0.1 [e]
	Lithium (Li)	mg/L	0.35	2.5 [d]
	Magnesium (Mg)	mg/L	1,370	na
	Manganese (Mn)	mg/L	1.75	0.2 [d]
	Mercury (Hg)	mg/L	0.00005	0.000026 [b2]. 0.000016 [c2], 0.003 [e]
	Molybdenum (Mo)	mg/L	0.0187	0.073 [b2], 0.01 [d], 0.5 [e]
	Nickel (Ni)	mg/L	0.0014	0.5 [a1], 1 [a2], 0.025-0.068 [b2,E], 0.2 [d], 1 [e]
	Potassium (K)	mg/L	245	na
	Selenium (Se)	mg/L	0.002	0.001 [b2], 0.02 [d], 0.05 [e]
	Sodium (Na)	mg/L	8,980	na

Parameters		Units	75th Percentile [n= 19 to 29 (1)]	MMER and CCME Guidelines
Dissolved Metals *(cont'd)*	Strontium (Sr)	mg/L	27.6	na
	Uranium (U)	mg/L	0.00006	0.033 [b1], 0.015 [b2], 0.01 [d], 0.2 [e]
	Zinc (Zn)	mg/L	0.157	0.5 [a1], 1 [a2], 0.03 [b2], 5 [d], 50 [e]

Source: \\VAN-SVR0\Projects\01_SITES\Hope.Bay\!Project_Data (Not Job Specific)\04 Groundwater Chemistry\!Master WQ Database\ !MASTER Hope Bay Water Chemistry DB_jm_ja_spb Rev16.xlsx

Notes:

[1] *n, count of values used to calculate statistics. Statistics were calculated by assuming that all values below detection limit were at the detection limit. Some samples taken early in the program had high detection limits and were therefore excluded from the statistical summary.*

[a1] *MMER Maximum authorized monthly mean concentration*

[a2] *MMER Maximum authorized concentration in a grab sample*

[b1] *CCME Freshwater (Short term)*

[b2] *CCME Freshwater (Long term)*

[c1] *CCME Marine (Short term)*

[c2] *CCME Marine (Long term)*

[d] *CCME Irrigation*

[e] *CCME Livestock*

[A] *Cadmium short term guideline concentration =* $10^{[1.016(\log[hardness])-1.71]}$ *µg/L for hardness ≥5.3 and ≤360 mg/L and the long term guideline =* $10^{[0.83(\log[hardness])-2.46]}$ *µg/L for hardness ≥17 to ≤280 mg/L*

[B] *Chromium Hexavalent 0.001 mg/L and Chromium Trivalent 0.0089 mg/L*

[C] *Copper guideline concentration =* $0.2 * e^{\{0.8545[\ln(hardness)]-1.465\}}$ *µg/L for hardness ≥82 to ≤180 mg/L and for hardness <82 mg/L a concentration of 2 µg/L applies*

[D] *Lead guideline concentration =* $e^{\{1.273[\ln(hardness)]-4.705\}}$ *µg/L for hardness*

[E] *Nickel guideline concentration =* $e^{\{0.76[\ln(hardness)]-1.06\}}$ *µg/L for hardness >60 to ≤80 mg/L and for hardness ≤60 mg/L a concentration of 25 µg/L applies*

[F] *Total ammonia guideline pH and temperature dependent*

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