PHASE 2
DRAFT 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.

mbgs	Metres below ground surface
NRCAN	Natural Resources Canada
ppt	Parts per thousand
the Project	Hope Bay Project

6. Permafrost

6.1 INTRODUCTION

This chapter describes baseline permafrost conditions at the Hope Bay Project (the Project).

Permafrost is a thermal condition of earth material (soil, organics, and rock) that remains at or below 0°C for at least two consecutive years including the intervening thaw season. Permafrost may have formed tens to hundreds of thousands of years ago, or more recently under current climate. Over time, permafrost naturally responds to climate and changes in surface conditions.

Figure 6.1-1 shows a simplified ground thermal regime in permafrost environments. The active layer is defined as the uppermost layer of ground that seasonally thaws and freezes in areas underlain by permafrost. Below the active layer, the permafrost body remains perennially below 0°C. Soils in permafrost environments vary from dry ice-poor sediments to ice-rich material with massive ground ice upwards of 20 meters thick. The base of permafrost represent the deepest position in the ground where 0°C is measured. The presence of saline groundwater may depresses the freezing point and result in unfrozen ground above the base of permafrost.

6.2 REGIONAL SETTING

The Project site is situated north of treeline within the zone of continuous permafrost (Brown et al. 2002). Regionally, ground ice is mapped as being low when compared to other areas of Canada where significant amounts of massive ground ice are present. Massive ice in the form of tabular ice bodies and ice wedges are mapped as sparse for the region, resulting in a low thaw settlement potential (Smith 2001). Smith and Burgess (2004) predict the region to be thermally sensitive to climate change, with low physical response resulting from thaw. At a local scale ground ice can be highly variable and site geotechnical investigations are conducted to evaluate site-specific permafrost and ground ice conditions.

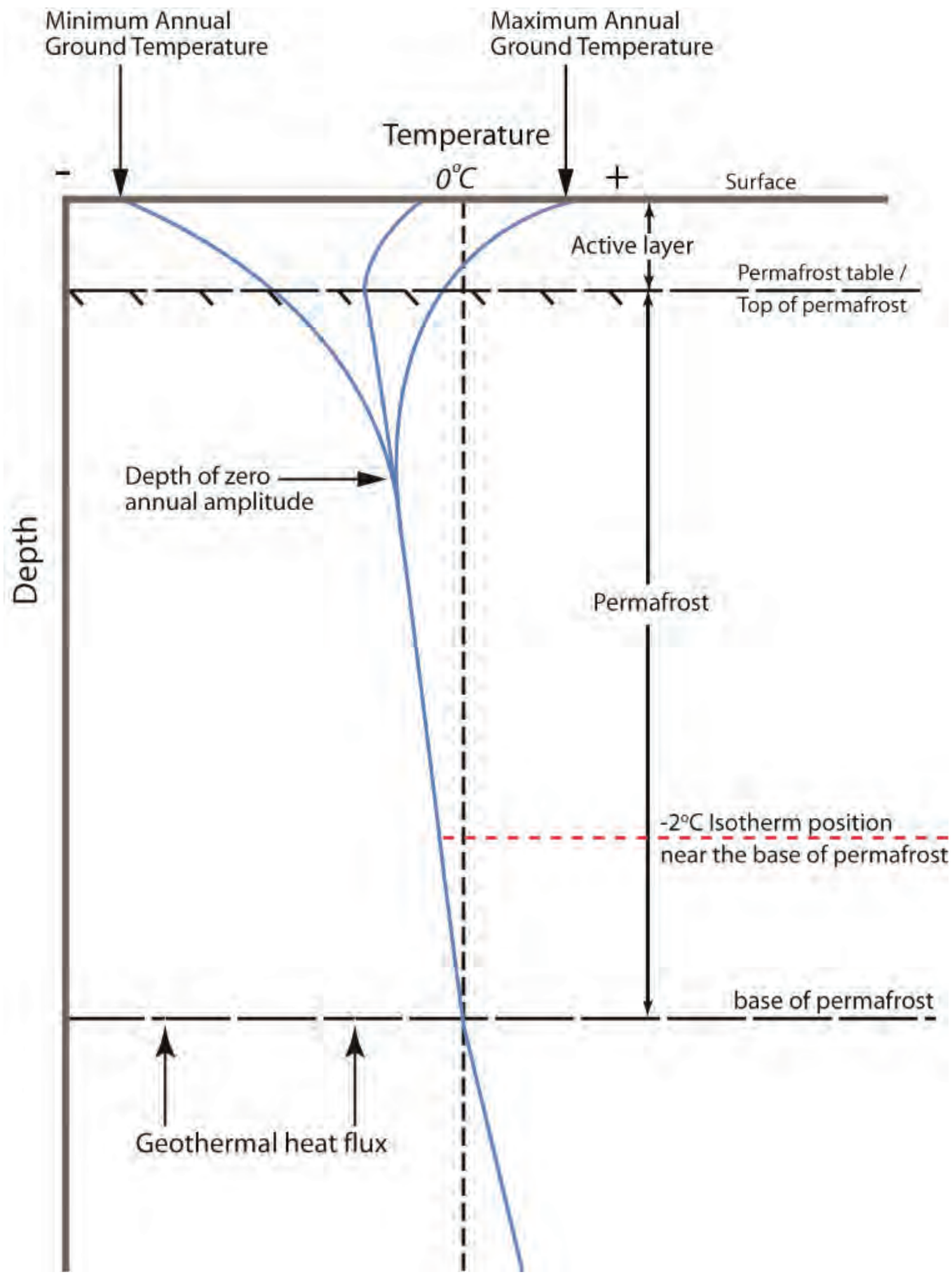
6.3 EXISTING ENVIRONMENT AND BASELINE INFORMATION

6.3.1 Data Sources

The understanding of permafrost at the Project site is based on information collected as part surficial geology and geotechnical investigations. The most relevant investigation include:

1. Surficial geology and permafrost feature mapping that has been conducted since 1992. The primary sources for characterisation of overburden and permafrost features include: J.M. Ryder & Associates (1992), EBA (1993; 1996; 1998); SRK (2002a), Sherlock (2002), Thurber (2003); and SRK (2009a).
2. Major onshore geotechnical studies have been conducted since 1996 to understand overburden conditions at the Project site include: EBA (1996; 1997), and SRK (2002b; 2003; 2005a; 2005b; 2005c; 2005d; 2006a; 2006b; 2010; 2012; 2015).
3. Thermistor cables (strings) have been installed to measure ground temperature at the Project site. Baseline thermistor cables installed as part of the field studies include: EBA (1996; 1997), SRK (2002b; 2003; 2005a; 2005b; 2005d; 2009a; 2009b; 2009c; 2009d; 2011).

Ground Thermal Regime in Permafrost Environments



6.3.2 Methods

Site Instrumentation

A total of 42 thermistor cables have been installed for the purpose of collecting baseline ground temperature measurements at the Project site. Table 6.3-1 provide a list of baseline ground temperature sites which include 32 sites at the Doris Mining Area, three sites at Madrid, seven sites at Boston, and four sites near Roberts Bay with sufficient data for analysis. Figures 6.3-1 through 6.3-3 show the location of thermistor cables at Doris Mine, and Madrid and Boston Mining Areas, respectively.

At most sites, NQ boreholes were drilled and cased with 2.54-cm diameter schedule 80 PVC pipe. The annulus between the borehole wall and PVC casing was backfilled with sand. A larger diameter HW steel casing (outside diameter of 11.4 cm) was set over the PVC pipe and hammered to about 50 cm below the ground surface as means of protecting the site. The thermistor cables were installed in the air-filled PVC casings and attached to a terminal switch box to allow for measurement of each thermistor node (sensor) on the cable.

Thermistor cables installed at the Project site include shallow, mid-depth, and depth cables. Three Westbay multi-point deep monitoring wells (10WBW001, 10WBW002 and 10WBW004) also provide baseline ground temperature at the Project site (SRK 2011).

Ground temperature measurements were manually collected with a handheld resistance meter which was attached to the terminal switch box. The measured resistance was converted to temperature using the Steinhart-Hart equation and factory calibration coefficients which were established prior to cable installation. The factor calibrated thermistor nodes typically have an accuracy of +/- 0.1ºC.

The measurement frequency and length of the data record for the baseline ground temperature sites is variable due to the remoteness of the site which can limit access and instrument damage caused by animals. Damage to individual thermistor nodes or lead wires during installation or over the life of the cable is expected to occur, and several baseline sites are inactive due to construction of infrastructure since installation.

Permafrost Characterization and Delineation

Ground temperature measurements were analyzed to determine:

- Active layer thickness;
- Permafrost temperature;
- Base of the permafrost; and
- Geothermal gradient within the permafrost.

The thickness of the active layer was estimated by interpolating the depth between the deepest thermistor node indicating thaw (greater than 0°C) and the shallowest sensor perennially frozen (less than 0°C) at the time of the year when summer thaw attained its greatest depth below the surface (typically between mid-August to mid-September). At some sites, thermistor cables nodes were not installed within the seasonally thawed active layer and the uppermost sensor was located within the top of the permafrost. For these cases, active layer thickness could not be calculated and the thickness is expressed as being less than uppermost sensor located at the top of permafrost.

Figure 6.3-1

Doris Mining Area Baseline Ground Temperature Sites

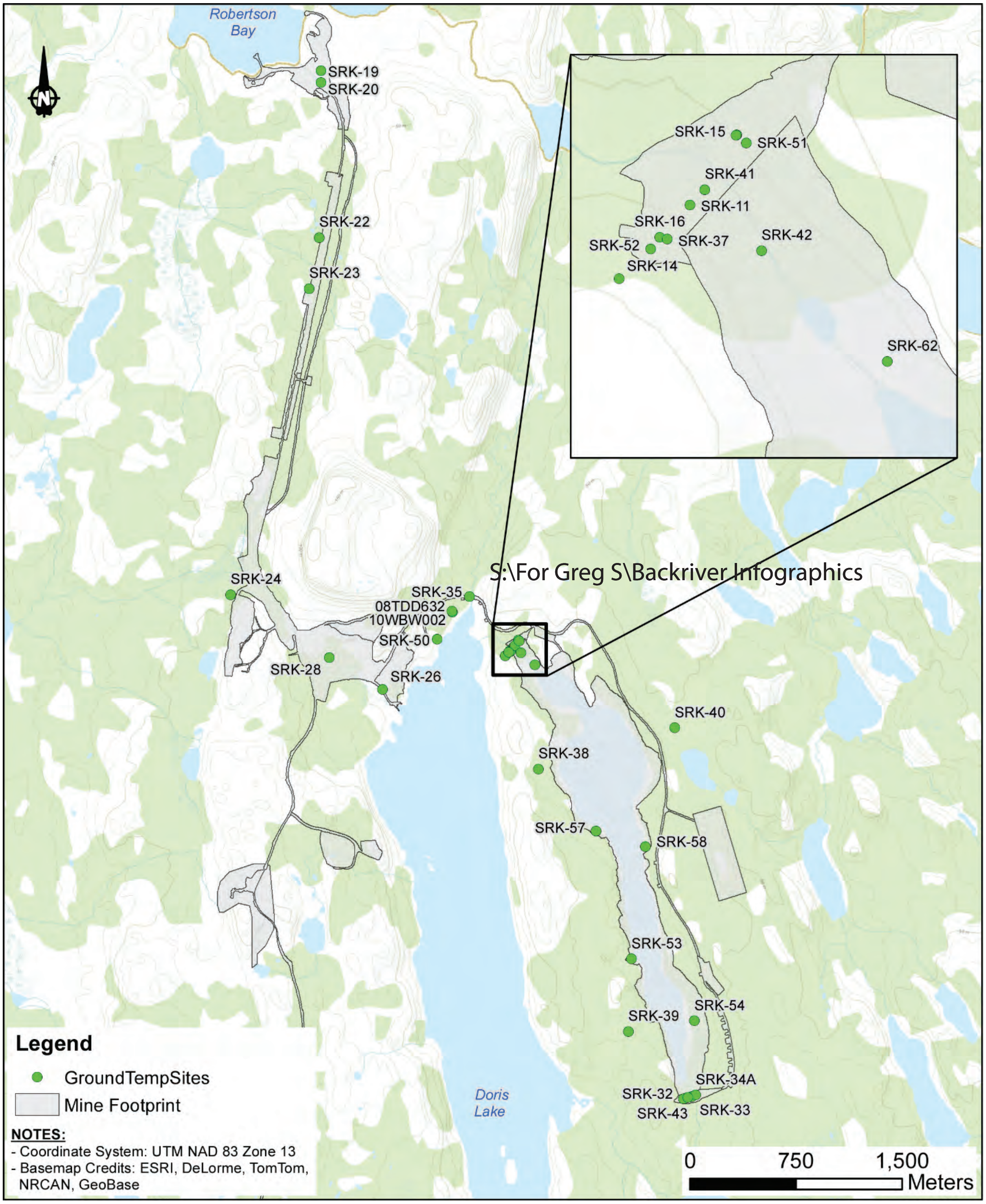


Table 6.3-1. Permafrost Characteristics for Baseline Sites

Station ID	Northing	Easting	Location	Area	Data Exclusion and Limitations (See Notes)	ALT Average (m)	ALT Minimum (m)	ALT Maximum (m)	AL n	Geothermal Gradient (°C/m)	-2°C Isotherm (mbgs)	Base of Permafrost, 0°C isotherm (mbgs)	Permafrost Temperature (°C)
SRK-11	7,559,117	434,347	North Dam	Doris Mining Area	1,4,5	<3.8	-	-	-	-	-	-	-7.9
SRK-13	7,559,172	434,383	North Dam	Doris Mining Area	6	-	-	-	-	-	-	-	-
SRK-14	7,559,059	434,292	Near North Dam	Doris Mining Area	1,5	1.3	1.0	1.4	11	-	-	-	-9
SRK-15	7,559,172	434,383	North Dam	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-8.1
SRK-16	7,559,092	434,323	North Dam	Doris Mining Area	1,4,5	<3.3	-	-	-	-	-	-	-9.8
SRK-19	7,563,212	432,984	Beach Laydown Area	Roberts Bay	1,4,5	<0.9	-	-	-	-	-	-	-7.6
SRK-20	7,563,130	432,986	Beach Laydown Area	Roberts Bay	1,5	0.9	0.7	1.1	4	-	-	-	-7.3
SRK-22	7,562,027	432,972	East of Doris Airstrip	Roberts Bay	1,4,5	<0.7	-	-	-	-	-	-	-7.7
SRK-23	7,561,666	432,902	South Apron Doris Airstrip	Roberts Bay	1,4,5	<0.9	-	-	-	-	-	-	-7.9
SRK-24	7,559,494	432,344	Near crusher at Q2	Doris Mining Area	1,4,5	<0.7	-	-	-	-	-	-	-7.3
SRK-26	7,558,820	433,422	Junction Doris Rd and Tail Lk Road	Doris Mining Area	1,4,5	<0.8	-	-	-	-	-	-	-8.8
SRK-28	7,559,046	433,043	Camp Pad	Doris Mining Area	1,4,5	<0.8	-	-	-	-	-	-	-8.1
SRK-32	7,555,915	435,555	South Dam Area	Doris Mining Area	1,5	1.1	0.9	1.4	7	-	-	-	-8.4
SRK-33	7,555,930	435,614	South Dam Area	Doris Mining Area	1,4,5	<0.7	-	-	-	-	-	-	-8.7
SRK-34A	7,555,942	435,641	South Dam Area	Doris Mining Area	1,4,5	<0.9	-	-	-	-	-	-	-8.1
SRK10-DCB2	7,559,478	434,037	Doris Creek Bridge Abutment East	Doris Mining Area	2	-	-	-	-	-	-	-	-
SRK10-DCB1	7,559,475	434,068	Doris Creek Bridge Abutment West	Doris Mining Area	2	-	-	-	-	-	-	-	-
SRK-35	7,559,478	434,036	Doris Creek - West	Doris Mining Area	1,5	0.5	0.5	0.5	2	-	-	-	-6.2
SRK-37	7,559,091	434,329	North Dam	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-8.2
SRK-38	7,558,254	434,526	Tail Lake West Side	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-8.1
SRK-39	7,556,391	435,164	Tail Lake West Side	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-7.7
SRK-40	7,558,547	435,492	Tail Lake East Side	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-8.7
SRK-41	7,559,129	434,359	North Dam Area	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-7.2
SRK-42	7,559,081	434,403	North Dam Area	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-8
SRK-43	7,555,924	435,585	South Dam Area	Doris Mining Area	1,3,5	-	-	-	-	-	-	-	-8.7
SRK-50	7,559,177	433,807	Doris Lake North End	Doris Mining Area	1,3	-	-	-	-	0.019	-	-	-5.6
SRK-51	7,559,166	434,391	North Dam Area	Doris Mining Area	1,5	0.7	0.6	0.7	3	-	-	-	-
SRK-52	7,559,083	434,316	North Dam Area	Doris Mining Area	1,5	0.7	0.7	0.8	3	-	-	-	-
SRK-53	7,556,907	435,184	Tail Lake West Side	Doris Mining Area	1,5	1.0	0.8	1.2	6	-	-	-	-6.6
SRK-54	7,556,467	435,632	Tail Lake East Side	Doris Mining Area	1,5	1.2	1.1	1.3	4	-	-	-	-6.9
SRK-55	7,557,813	434,936	Tail Lake West Side	Doris Mining Area	6	-	-	-	-	-	-	-	-
SRK-56	7,558,258	435,334	Tail Lake East Side	Doris Mining Area	6	-	-	-	-	-	-	-	-
SRK-57	7,557,812	434,938	Tail Lake West Side	Doris Mining Area	1,4,5	<3.3	-	-	-	-	-	-	-8.1
SRK-58	7,557,705	435,285	Tail Lake East Side	Doris Mining Area	1,5	1.0	0.9	1.1	2	-	-	-	-7
SRK-62	7,558,995	434,501	Tail Lake North End	Doris Mining Area	1,5	0.9	0.9	1.0	4	-	-	-	-
TM00141	7,546,691	435,141	Patch Lake	Madrid Mining Area	1,3,5	-	-	-	-	0.023	303	346	-
SRK-JT1-09	7,563,297	432,534	Jetty	Roberts Bay Jetty	2	-	-	-	-	-	-	-	-
SRK-JT2-09	7,563,264	432,550	Jetty	Roberts Bay Jetty	2	-	-	-	-	-	-	-	-
SRK-JT2-12	7,563,264	432,550	Jetty	Roberts Bay Jetty	2	-	-	-	-	-	-	-	-

Station ID	Northing	Easting	Location	Area	Data Exclusion and Limitations (See Notes)	ALT Average (m)	ALT Minimum (m)	ALT Maximum (m)	AL n	Geothermal Gradient (˚C/m)	-2˚C Isotherm (mbgs)	Base of Permafrost, 0˚C isotherm (mbgs)	Permafrost Temperature (˚C)
08SBD380	7,504,780	441,080	South of Boston Site	Boston Mining Area	1,3	-	-	-	-	0.017	430	565	-7.1
08SBD381A	7,504,814	441,070	South of Boston Site	Boston Mining Area	1,3	-	-	-	-	0.029	202	281	-6.1
08SBD382	7,505,141	441,026	South of Boston Site	Boston Mining Area	1,3	-	-	-	-	0.027	224	302	-6.2
08PMD669	7,550,955	433,300	Between Patch and Windy Lakes (N)	Madrid Mining Area	1,3	-	-	-	-	0.018	438	570	-7.6
08PSD144	7,548,990	435,178	Patch Lake Island	Madrid Mining Area	1,5,8	-	-	-	-	-	50	78	-
08TDD632	7,559,370	433,915	West Side Doris Lake N	Doris Mining Area	1	-	-	-	-	0.024	315	445	-6.7
08TDD633	7,557,646	433,402	West Side Doris Lake	Doris Mining Area	6	-	-	-	-	-	-	-	-
10WBW001	7,557,537	433,778	Beneath Doris Lake	Doris Mining Area	7	-	-	-	-	-	-	-	-
10WBW002	7,559,375	433,913	Doris Site	Doris Mining Area	1,3,5	-	-	-	-	0.014	358	511	-7.1
10WBW004	7,505,665	441,018	Boston Site	Boston Mining Area	1,3	-	-	-	-	0.018	209	326	-6.1
12259-97-01 / DH#1	7,565,768	431,165	Onshore West Side of Roberts Bay	Roberts Bay	6	-	-	-	-	-	-	-	-
12259-97-8 / DH#8	7,565,625	431,130	Onshore West Side of Roberts Bay	Roberts Bay	8	-	-	-	-	-	-	-	-
12259-97-17 / DH#17	7,565,520	431,211	Onshore West Side of Roberts Bay	Roberts Bay	8	-	-	-	-	-	-	-	-
12259-03	7,504,380	441,113	Boston Site	Boston Mining Area	1,5	0.9	0.8	0.9	2	-	-	-	-7.0
12259-05	7,504,778	441,172	Boston Site	Boston Mining Area	6	-	-	-	-	-	-	-	-
12259-96-06	7,505,683	441,327	Boston Site	Boston Mining Area	1,5	1.7	1.6	1.7	2	-	-	-	-7.8
97NOD176	7,504,962	441,481	Boston Site	Boston Mining Area	1,3,5	-	-	-	-	0.019	449	556	-9.0
CX3(3)-13	-	-	Boston UG Workings	Boston Mining Area	6	-	-	-	-	-	-	-	-
TDD-242	-	-	-	Doris Mining Area	8	-	-	-	-	-	-	-	-
TDD-261	-	-	-	Doris Mining Area	6	-	-	-	-	-	-	-	-
DB#27-H	-	-	Boston UG Workings	Boston Mining Area	6	-	-	-	-	-	-	-	-
DB#27-V	-	-	Boston UG Workings	Boston Mining Area	6	-	-	-	-	-	-	-	-
DB#36	-	-	Boston UG Workings	Boston Mining Area	6	-	-	-	-	-	-	-	-
SRK-12-GTC-DH01	7,558,917	433,169	Contact Water Pond	Doris Mining Area	2	-	-	-	-	-	-	-	-
SRK-12-GTC-DH02	7,558,913	433,225	Contact Water Pond	Doris Mining Area	2	-	-	-	-	-	-	-	-
SRK-12-GTC-DH03	7,558,931	433,225	Contact Water Pond	Doris Mining Area	2	-	-	-	-	-	-	-	-
SRK10-DWB1	7,555,674	432,703	Doris-Windy Road Bridge #2	Madrid Mining Area	2	-	-	-	-	-	-	-	-
SRK10-DWB2	7,555,644	432,708	Doris-Windy Road Bridge #2 / #3	Madrid Mining Area	2	-	-	-	-	-	-	-	-
SRK10-DWB3	7,556,150	432,713	Doris-Windy Road Bridge #3	Madrid Mining Area	2	-	-	-	-	-	-	-	-
SRK10-DWB4	7,554,860	432,444	Doris-Windy Road Bridge #4	Madrid Mining Area	2	-	-	-	-	-	-	-	-
SRK10-DWB5	7,554,831	732,437	Doris-Windy Road Bridge #4	Madrid Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-040-31.5	7,559,101	434,324	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-040-33.5	7,559,101	434,324	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-040-KT	7,559,101	434,324	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-060-DS	7,559,115	434,338	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-060-33.5	7,559,115	434,338	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-060-31.0	7,559,115	434,338	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-060-28.8	7,559,115	434,338	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-060-KT	7,559,115	434,338	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-060-US	7,559,107	434,346	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-085-DS	7,559,134	434,354	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-

Station ID	Northing	Easting	Location	Area	Data Exclusion and Limitations (See Notes)	ALT Average (m)	ALT Minimum (m)	ALT Maximum (m)	AL n	Geothermal Gradient (°C/m)	-2°C Isotherm (mbgs)	Base of Permafrost, 0°C isotherm (mbgs)	Permafrost Temperature (°C)
ND-HTS-085-25.3	7,559,134	434,354	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-085-29.4	7,559,134	434,354	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-085-33.5	7,559,134	434,354	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-085-KT	7,559,134	434,354	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-085-KT	7,559,134	434,354	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-085-US	7,559,125	434,363	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-130-DS	7,559,167	434,384	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-130-28.8	7,559,167	434,384	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-130-31.0	7,559,167	434,384	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-130-33.5	7,559,167	434,384	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-130-KT	7,559,167	434,384	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-130-US	7,559,158	434,394	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-175-32.5	7,559,201	434,415	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-HTS-175.33.5	7,559,201	434,415	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
ND-VTS-175-KT	7,559,201	434,415	North Dam	Doris Mining Area	2	-	-	-	-	-	-	-	-
					Average	**1.0**	**-**	**-**	**-**	**0.021**	**298**	**398**	**-7.6**
					Minimum	**-**	**0.5**	**-**	-	**0.014**	**50**	**78**	**-9.8**
					Maximum	**-**	**-**	**1.7**	-	**0.029**	**449**	**570**	**-5.6**
					Number of samples	**12**	**12**	**12**	**50**	**10**	**10**	**10**	**37**

Notes:

Table Headings

1. *Station ID - Thermistor cable identification*
2. *Northing and Easting - Universal Transverse Mercator coordinates for Stations (UTM NAD 83 Zone 13 N)*
3. *Location and Area provides descriptive location of the Station*
4. *Data Exclusion and Limitations index provided below*
5. *ALT Average - Average active layer thickness calculated for years with suitable data*
6. *ALT Minimum - Minimum active layer thickness calculated for years with suitable data*
7. *ALT Maximum - Maximum active layer thickness calculated for years with suitable data*
8. *AL n - Number of individual years with data suitable for active layer measurement*
9. *Geothermal Gradient - Calculated thermal gradient of deep permafrost for depths greater than 100 m*
10. *Base of Permafrost - Estimated bottom position of permafrost based on 0°C isotherm*
11. *Permafrost Temperature - Calculated between 8 and 33 m below ground surface based on data availability*

Data Exclusion and Limitations Index

1. *Baseline data used for permafrost characterization and statistics*
2. *Data excluded, monitoring site is not part of baseline monitoring*
3. *Measurement frequency, sensor position, and/or spacing not appropriate for estimation of active layer thickness*
4. *Active layer thickness constrained by upper sensor located within permafrost, value not included in statistics*
5. *Sensor position not appropriate for calculation of select permafrost characteristics*
6. *Insufficient data for analysis*
7. *Permafrost absent at instrumented site*
8. *Data in graphical form and not digital for exact calculation of temperature*

Figure 6.3-2

Madrid Mining Area Baseline
Ground Temperature Sites

Figure 6.3-3
Boston Mining Area Baseline Ground Temperature Sites

Permafrost temperature was calculated as the average temperature for nodes located at a positon between 8 and 33 m. These depths are around the depth of zero annual amplitude; i.e. the position in the ground where seasonal variability in ground temperature is less than 0.1°C (Figure 6.1-1). Permafrost temperature from this position is less influenced by the frequency and time of the year over which the individual measurements were made. The depth of zero annual amplitude modeled for clay soils with an organic cover was assessed to range from 17 to 19 mbgs.

The geothermal gradient was calculated from ground temperature measurements below the depth of zero annual amplitude. Data for calculation of the geothermal gradient for the lower section of permafrost was available between 130 and 489 mbgs. The base of permafrost was determined by extrapolating the geothermal gradient from the deepest node to a temperature of 0ºC, or by interpolating the position between nodes with a temperature above and below 0ºC.

6.3.3 Permafrost Characteristics

6.3.3.1 Permafrost Soil Properties

Laboratory and in-situ testing of disturbed and undisturbed geotechnical samples collected during previous drilling campaigns confirm that onshore overburden soils are comprised mainly of marine clays, silty clay and clayey silt, with pockets of moraine till underlying these deposits. The overburden profile consists of a thin veneer of hummocky organic soil covered by tundra heath vegetation. Typically this layer is poorly drained. Under the organic cover is a layer of marine clay (silty clay and clayey silt) typically between 5 and 20 m thick; however, since the terrain is glaciated with significant bedrock control, there are areas where overburden is less than 5 m thick as well as areas where the overburden exceeds 30 m in thickness. The most prevalent rock type on site with surface exposure is mafic volcanics, predominantly basalt. In isolated locations there are small amounts of gabbro, felsic volcanic and granitoids.

The marine silts and clays contain ground ice which on average ranges from 10 to 30% by volume, but occasionally may be as high as 50%. Till at the Project site typically contains low to moderate ice contents ranging from 5 to 25%. The bedrock contact zone generally consists of a small rubble zone ranging from a few centimetres to up to 2 m in thickness.

The overburden soil pore water typically has high salinity concentrations, often exceeding that of seawater due to inundation by seawater following deglaciation of the area. This has the effect of depressing the freezing point, as well as contributing to a high unfrozen water content. The average site-wide pore water salinity is 37 parts per thousand (ppt) with a calculated freezing point of -2.1°C (Geometric mean of 25 ppt with a freezing point of -1.4°C). The average pore water freezing point is -0.8°C for sand samples and -2.2°C for silt and clay samples. Additional statistics on the pore water salinity from soil samples collected at the Project site is presented in Appendix V3-2E, Geotechnical Design Parameters and Overburden Summary Report.

The high porewater salinity concentrations in the overburden also contribute to high unfrozen water contents. Unfrozen water content testing of clay and silt performed in 2004 and 2005 (SRK 2005a and 2005b) indicates that the unfrozen water content at −5°C ranges from 31% to 90% by total volume; this decreases to 23% to 63% at −10°C. A low unfrozen water content is expected for sand due to the low porewater salinity measured at the Project site and the general freezing characteristics of coarse-grained material, such as sand and gravel.

6.3.3.2 Permafrost Temperature

The Project site is located within the continuous permafrost region of western Nunavut. The average permafrost temperature measured at the Property is -7.6°C, with a range from -5.6°C to -9.8°C (Table 6.3-1). These statistics are based temperature measurements near the depth of zero annual amplitude from 37 baseline sites located in the Doris Mine, and the Madrid and Boston mining areas. The baseline ground temperature sites do not permit for separate assessment of permafrost temperatures at each of the three mining areas. Permafrost temperatures naturally vary across the Project site in response to microclimatic effects such as surface vegetation, moisture content, and soil properties.

6.3.3.3 Active Layer Thickness

Active layer thickness is spatially and temporarily variable due to local differences in climate, overburden type, surface moisture, vegetation and organic cover, and snow cover across the Project site. Average active layer thickness is calculated to be 1.0 m over the period of record, with a range from 0.5 m to 1.4 m (Table 6.3-1).

6.3.3.4 Base of Permafrost and Geothermal Gradient

The average depth to the base of permafrost is 398 mbgs based on ten sites at the Project site, with a range from 78 mbgs to 570 mbgs depending on proximity to waterbodies (Table 6.3-1). Average depth to the base of permafrost outside of the thermal influence of waterbodies is 529 mbgs. The geothermal gradient of the lower section of permafrost is calculated to average 0.021°C m^{-1}, with a range of 0.014°C m^{-1} to 0.029°C m^{-1} (Table 6.3-1).

6.3.4 Lake Taliks

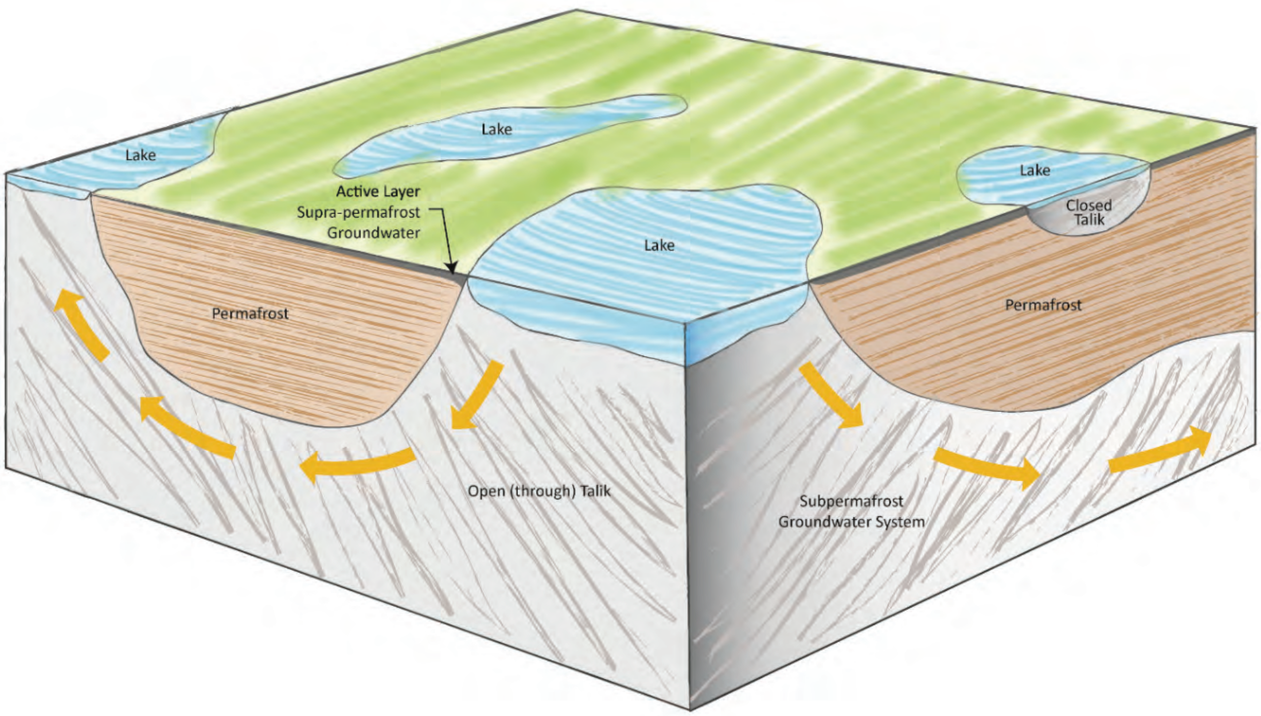
A talik is defined as “a layer or body of unfrozen ground occurring in a permafrost area due to local anomalies in thermal, hydrological, hydrogeological or hydrochemical conditions” (van Everdingen 2005). Taliks are commonly present beneath lakes in permafrost environments due to the local departure in terrestrial ground temperature caused by surface water (Smith and Hwang 1973; Burn 2002).

Lake taliks may be classified as closed and open (through) taliks; a closed talik is an unfrozen zone beneath a water body that is enclosed at the base and the surrounding sides by ice-bonded permafrost; and an open talik is an unfrozen zone beneath a water body that penetrates the ice-bonded permafrost completely and may connect suprapermafrost (i.e. the layer of ground above permafrost) and sub-permafrost (i.e. the unfrozen ground below the permafrost) groundwater (Figure 6.3-4).

Talik can generally be expected below lakes with depths greater than two thirds of the maximum thickness of ice forming annually on their surface (Mackay 1992; Burn 2002). The mean water bottom temperature, lake half width (or radius), and the surrounding terrestrial ground thermal regime are key variables that influence talik configuration and extent. Water bathymetry can also effect 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 2010a; 2010b).

The long-term thermal and physical evolution of the landscape is also factor in the present-day configuration of taliks that may extend hundreds of metres below the surface. Lunardini (1995) showed temperature at depths up to 600 mbgs can be influenced by surface temperatures as far back as 100,000 years. Smith and Hwang (1973) showed response of river taliks to channel migration and vegetation succession.

Conceptual Drawing showing Open (through) Taliks and Closed Taliks



The location of open taliks is important for the understanding of groundwater flow processes. The critical lake dimension required for open (through) lake taliks was assessed using a one-dimensional (1D) steady state analytical model for lakes (regional talik model). Site-specific talik modeling was also completed using numerical finite elements models for underground mining areas where greater detail of talik configuration was required.

Regional Talik Model

The regional thermal models used for this assessment are presented by Mackay (1962), Smith (1976), and Burn (2002) for study sites in the Canadian Arctic, and have been used for talik characterization at other proposed mine projects located in the continuous permafrost region of mainland Nunavut, including the Back River project (SRK 2015), Meliadine (Golder 2013), Kiggavik (Areva Resources Canada 2011), High Lake (Wolfden Resources Inc. 2006), Doris (SRK 2005b), and Meadowbank (Cumberland Resources Ltd. 2005) projects. The models examined the influence of lake geometry, lake-bottom temperature, and permafrost temperature. Where applicable, average values measured at the Project site were used as inputs for the talik models.

The critical lake dimension required for an open (through) taliks was assessed using a one-dimensional (1D) analytical models for lakes. The temperature profile beneath the centre of a circular lake without terraces has been modeled by Mackay (1962) as:

$$T_z = T_g + \frac{z}{I} + (T_p - T_g)\left(1 - \frac{z}{\sqrt{z^2+R^2}}\right) \qquad \text{Equation 1}$$

Where:

- Tz = temperature at depth z (ºC)
- LbT = Average annual lake bottom water temperature (˚C)
- Tg = average annual ground temperature (ºC)
- I = inverse of the geothermal gradient (m $ºC^{-1}$)
- z = depth below bottom of lake (m)
- R = radius of the lake (m)

The temperature profile beneath symmetrical elongated lakes without terraces has been modeled by Smith (1976) as:

$$T_z = T_g + \frac{z}{I} + \frac{T_p - T_g}{\pi}\left(2\tan^{-1}\frac{w}{z}\right) \qquad \text{Equation 2}$$

Where:

- T_z = Temperature at depth z (ºC)
- LbT = Average annual lake bottom water temperature (˚C)
- T_g = Average annual ground temperature (ºC)
- I= inverse of the geothermal gradient (m $ºC^{-1}$)
- z = depth below bottom of lake (m)
- w = half-width of an elongated lake

For conservatism, shallow-water terraces (lake terraces) which may be thermally influenced by bottom-fast ice were not considered in the analytical model.

Table 6.3-2 shows average lake bottom water temperatures for the months of April, July, August, and September for five lake locations measured over the period of 2010 to 2014. The lake bottom temperatures reflect the deepest measurement collected at each site. Mean annual lake bottom water temperature was calculated as a weighted mean of April and August temperature:

$LbT = 8LbTAp + 4LbTAug\ /P$ Equation 3

Where:

LbT – Average annual lake bottom water temperature (˚C)
$LbTApr$ – measured lake bottom water temperature in April (˚C)
$LbTAug$ – measured lake bottom water temperature in August (˚C)
P – is the period of time in months

Table 6.3-2. Summary of Lake Bottom Temperatures and Ice Thickness

Location	Data Source (see notes)	Temperature (˚C)					Ice Thickness (m)
		April	July	August	September	LbT	
Doris Lake North	1,3,4,5,6	1.5	7.8	11.0	6.2	4.7	1.8
Doris Lake South	1,3,4,5,6	1.0	9.0	10.7	5.7	4.2	1.9
Reference Lake A	1	1.6	-	4.3	-	2.5	1.8
Reference Lake B	1,3,4,5,6	2.6	9.1	11.1	3.9	5.5	1.7
Reference Lake C	2	2.0	-	8.3	-	4.1	1.9
Reference Lake D	1,3,4,5,6	0.8	11.4	12.1	2.5	4.6	1.9
Little Roberts Lake	1,3,4,5,6	0.7	10.6	10.9	3.4	4.1	1.9
Wolverine Lake	1	1.4	-	13.2	-	5.3	1.8
Patch Lake North	1	1.2	-	10.8	-	4.4	2.1
Patch Lake South	1	2.1	-	10.3	-	4.8	1.9
P.O. Lake	1	0.2	-	10.0	-	3.5	1.9
Ogama Lake	1	1.8	-	10.0	-	4.5	1.8
Doris Lake North	1	1.1	-	10.0	-	4.1	2.0
Doris Lake South	1	0.9	-	9.7	-	3.8	2.0
Naiqunnguut Lake	1	1.4	-	10.2	-	4.3	1.9
Nkhatok Lake	1	0.4	-	11.7	-	4.2	1.9
Glenn Lake	1	0.5	-	9.9	-	3.6	2.0
Imniagut Lake	1	-	-	12.2	-	-	2.0
Little Roberts Lake	1	1.3	-	10.0	-	4.2	2.1
Stickleback Lake	2	1.1	-	11.2	-	4.5	1.8
Trout Lake	2	0.8	-	12.6	-	4.7	1.8
Windy Lake	1,2	2.0	-	10.1	-	4.7	1.8
Aimaokatalok Lake: Station 2	2	-	-	11.6	-	-	-
Aimaokatalok Lake: Station 5	2	0.0	-	14.8	-	4.9	1.8
Aimaokatalok Lake: Station 6	2	2.3	-	12.1	-	5.6	1.6
Aimaokatalok Lake: Station 11	2	0.1	-	12.1	-	4.1	1.6
Aimaokatalok Lake: Station 13	2	-	-	13.9	-	-	-
				All Sites	**Average**	**4.4**	**1.9**
					Minimum	**2.5**	**1.6**
					Maximum	**5.6**	**2.1**
					Count	**24**	**25**

Notes:
1. Average monthly temperature collected over the period of 2009-2014 (see data source)
2. Annual lake bottom temperature (LbT) calculated using Equation 3
3. Ice thickness measured from ice auger hole drilled in April
4. Data source: 1 - Rescan (2010), 2 - Rescan (2011a), 3 - Rescan (2011b), 4 - Rescan (2012), 5 - ERM Rescan (2014), 6 ERM (2015)

Based on Equation 3, April water temperatures are assumed to be representative of the period of ice cover (October to May). August water temperatures represent the warmest measurements and likely over-estimate water temperature throughout the ice-free period. As a result, a slightly more conservative water temperature is computed using this approach. The calculated annual lake bottom water temperature is calculate to range from +2.5°C to +5.6°C, with an average of +4.4°C.

Talik configuration considered the freezing point of groundwater at the Project site. Based on measured concentrations of dominant parameters, saline water is considered to induce a freezing point depression of -2°C (Volume 5 Section 2 Groundwater). These results are based on the most reliable groundwater quality observed at the Project site.

The estimated critical dimensions for open (through) taliks beneath lakes at the Project site are summarized in Tables 6.3-3 and 6.3-4, respectively. For the base case scenario, open taliks are estimated to occur beneath circular lakes with a diameter greater than 224 m (lake radius of greater than 112 m). For elongated lakes, the critical lake width is estimated to be greater than 104 m wide (lake half-width greater than 52 m).

Table 6.3-3. Circular Lake Critical Radius for Open (Through) Taliks Based on -2°C Isotherm

Permafrost temperature	Annual Lake Bottom Temperature (LbT)				
	+3.0°C	**+4.0°C**	**+4.4°C**	**+5.0°C**	**+6.0°C**
-9.0°C	169 m	159 m	155 m	151 m	144 m
-8.0°C	138 m	129 m	126 m	122 m	117 m
-7.6°C	123 m	115 m	112 m	109 m	104 m
-7.0°C	108 m	101 m	98 m	95 m	91 m
-6.0°C	80 m	74 m	72 m	70 m	67 m
-5.0°C	54 m	50 m	49 m	47 m	44 m

Table 6.3-4. Elongated Lake Critical Half-width for Open (Through) Taliks Based on -2°C Isotherm

Permafrost temperature	Annual Lake Bottom Temperature (LbT)				
	+3.0°C	**+4.0°C**	**+4.4°C**	**+5.0°C**	**+6.0°C**
-9.0°C	83 m	76 m	73 m	70 m	65 m
-8.0°C	66 m	60 m	58 m	55m	50 m
-7.6°C	60 m	54 m	52 m	49 m	45 m
-7.0°C	50 m	45 m	43 m	41 m	38 m
-6.0°C	36 m	32 m	30 m	28 m	26 m
-5.0°C	23 m	20 m	19 m	17 m	15 m

Site-specific Talik Model

Lake talik configuration adjacent to the Boston and Madrid mining areas was estimated using 2D thermal modeling. The model results were fitted to field observations of the -2°C isotherm, and therefore use calculated heat flow as a basis for estimating talik geometry based on measured temperatures at each site. The modeling was carried out using a finite element code SVHeat developed by SoilVision Systems Ltd. with the FlexPDE solver. 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 (Appendix V3-2D Water and Load

Balance). The model input and assumptions are presented in Appendix V3-4B Hydrogeological Characterization for Madrid North, Madrid South and Boston.

The site specific model is based on the following ground temperature measurements:

- At Boston three deep inclined wells, which extended beneath Aimaokatalok Lake (sites 08SBD381A, 08SBD382, 10WBW004, and two inland wells (sites 08SBD380 and 97NOD176). The two inland sites are considered to be outside of the thermal influence of Aimaokatalok Lake.
- At Madrid South and Madrid North three inclined wells (08PMD669, 08PSD144, and TM00141). Site 08PMD669 is located within the area of the Madrid North underground mine workings. Site TM00141 is located within the Madrid South underground mine between Wolverine Lake and Patch Lake. 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.

The detailed configurations of the open taliks adjacent to the Boston, Madrid South and Madrid North underground mining areas are presented in Appendix V3-4B Hydrogeological Characterization for Madrid North, Madrid South and Boston. Thermal analyses of talik configuration at the underground mining areas concluded:

- 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.

6.3.5 Impacts of Climate Change on Permafrost Conditions

Permafrost is a continuously changing component of Canada’s Arctic. Climate is a first-order control on the permafrost and microclimatic conditions which influence the ground thermal regime. Local permafrost conditions are impacted by air temperature, snow condition, vegetation characteristics, surface moisture, and other surface conditions.

At the Doris and Madrid mining areas, the mean annual air temperature is projected to increase by 6.8°C by the year 2100. Further inland at the Boston mining area, the air temperature is projected to increase by 5.5°C. The increase in air temperature is likely to cause natural permafrost degradation.

Smith and Burgess (2004) assessed the sensitivity of permafrost to climate warming in Canada by categorizing the response of ground thermal conditions to climate, and the effects of permafrost thaw on terrain stability. At the Project site, permafrost is regionally predicted to be thermally sensitive to climate change, with low physical response resulting from thaw (Smith and Burgess 2004). Permafrost, however, will be locally thaw-sensitive where ice-rich soils and massive ground ice are present. The Project site is however predicted to stay within the zone of continuous permafrost (ACIA 2005).

Active layer thickness is expected to increase in response to climate change at the Project site. By the year 2100, active layer thickness for areas with natural overburden clay is estimated to increase by 93 cm at the Project site, as determined using the long-term air temperature trends applied to numerical thermal conduction models. The temperature at the top of permafrost would also be expected to increase. Permafrost distribution is expected to remain continuous across the Project site over the life of the Project.

The warming of permafrost and lake water would be expected to result in increased lake talik extent over time. Talik expansion caused by climate change would be expected to be limited to the top tens of metres on the time scale of the Project due to the time requirements for heat to transfer deep into the ground. The most immediate effects expected would be an increase in lateral extent of the talik beneath the shoreline, and possible subsidence and erosion at locations with ice-rich permafrost. A reduction in ice growth would also be expected to widen and deepen existing taliks beneath shallow waterbodies which rely on seasonal heat loss though the establishment of bottom-fast ice (Burn 2002; 2005; Stevens 2010a; 2010b). The natural development of new ponds at the Project site may result in newly formed closed taliks over the period of mining. On the time scale of hundreds to thousands of years, open taliks may form as permafrost degrades beneath water bodies.

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