APPENDIX 27-A

Implications of Long-term Climate Conditions on Permafrost

TETRA TECH

TECHNICAL MEMO

ISSUED FOR USE

To:	James Scott, P.Eng., Engineering Manager, Goldcorp Inc.	**Date:**	January 19, 2017
c:	Kevin Jones, P.Eng., Tetra Tech Hongwei Xia, P.Eng., Tetra Tech	**Memo No.:**	001
From:	Chantal Pawlychka, E.I.T., Tetra Tech	**File:**	ENG.EARC03004-01
Subject:	Thermal Evaluation of Duration of Thaw of Permafrost Soils at Coffee Mine Site Study Area Under Long-term Climate Conditions, Yukon, Canada		

1.0 INTRODUCTION

Tetra Tech Canada Inc. (Tetra Tech) has been retained by Goldcorp Inc. (Goldcorp) to provide long-term permafrost related insight for the ground conditions encountered at the Coffee Gold Project (the project) study area (the site) in Yukon Territory, Canada. A long-term thermal evaluation was carried out under projected climate conditions to determine the duration of thaw of the permafrost rich soils and the embedded massive ice lenses existing at the mine site. This technical memorandum summarizes the analysis methodology, input parameters, and findings of the thermal analyses.

2.0 PROJECT SETTING

2.1 Site Location

The project site (62°52'N, 139°10'W) is located approximately 130 km south of Dawson City and within the Whitehorse Mining District in west-central Yukon Territory, Canada.

2.2 Permafrost Condition and Ground Temperature

Permafrost temperatures within the project site have been monitored since 2013 and range from -2°C to -0.6°C. The warmest permafrost temperature (-0.6ºC) was recorded at the bottom of the Halfway Creek valley. The coldest permafrost temperature (-2.0ºC) was recorded at the bottom of YT-24 Creek and on the north-facing slope of the upper Halfway Creek valley. The permafrost classification for the project site is thus "warm" and therefore the ground is sensitive to disturbance (Tetra Tech EBA 2016).

Permafrost thicknesses within the project site are highly variable, ranging from approximately 30 m to 165 m. Ground ice content (percent by volume) of the perennially frozen surficial materials is also highly variable (Tetra Tech EBA 2016). Some areas of the site are permafrost-free.

3.0 THERMAL CALIBRATION OF COFFEE MINE SITE STUDY AREA

3.1 General

Thermal analyses were carried out using Tetra Tech's proprietary two-dimensional finite element computer model, GEOTHERM. The model simulates transient, two-dimensional heat conduction with change of phase for a variety

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of boundary conditions. The heat exchange at the ground surface is modelled with an energy balance equation considering air temperatures, wind velocity, snow depth, and solar radiation. The model facilitates the inclusion of temperature phase change relationships for soils, so any freezing depression and unfrozen water content variations can be explicitly modelled. The model has been verified by comparing its results with closed-form analytical solutions and many different field observations. The model has successfully formed the basis for thermal evaluations and designs of tailings, dikes, foundations, pipelines, utilidor systems, landfills, and ground freezing systems in both arctic and subarctic regions since the 1980s.

3.2 Climatic Data

Only short-term data (2012 to 2016) is available at the project site. A meteorological station was installed at elevation 975 m asl by Access Consulting Group in July 2012 to collect baseline data including: air temperature and relative humidity, wind speed and direction, solar radiation, barometric pressure, and precipitation. The weather station was maintained by Access Consulting Group until May 2014. Lorax Environmental Services Ltd (Lorax) and Laberge Environmental Services has maintained the weather station from June 2014 to present (Lorax 2016a).

An extensive climate change study was carried out by Lorax to project the short site-specific climate record from the project site over a long-term period. The long-term synthetic temperature construction (1986-2015) was enabled by linking the project weather records to the long-term temperature conditions at the McQuesten and Pelly Ranch climate stations (Lorax 2016a). The long-term synthetic average monthly temperatures reflect a reasonable long-term regional record and were used to represent the project site.

The monthly wind speed, snow cover, and daily solar radiation data from the Minto Mine was adopted for the project site. The Minto Mine is located at elevation 875 m asl and is approximately 220 km southeast of the project site (Tetra Tech EBA 2011). The overall climate conditions experienced by the Minto Mine site are very comparable to the climate conditions experienced by the project site due to the similar elevation and location of the mine sites. The estimated long-term monthly mean climatic data at the project site are summarized in Table 1.

Table 1: Mean Climatic Conditions at Coffee Gold Project

Month	Synthetic Monthly Air Temperature (1986-2015) [(a)] (°C)	Monthly Wind Speed [(b)] (km/h)	Monthly Snow Cover [(c)] (m)	Daily Solar Radiation [(d)] (W/m^2)
January	-19.7	14.4	0.43	9
February	-14.9	21.6	0.52	40
March	-9.0	13.7	0.48	104
April	0.8	9.7	0.26	185
May	6.9	10.8	0	218
June	11.3	9.7	0	242
July	12.6	9.4	0	218
August	10.1	7.6	0	162
September	5.0	7.6	0	100
October	-2.4	9.4	0.06	45

Table 1: Mean Climatic Conditions at Coffee Gold Project

Month	Synthetic Monthly Air Temperature (1986-2015) [(a)] (°C)	Monthly Wind Speed [(b)] (km/h)	Monthly Snow Cover [(c)] (m)	Daily Solar Radiation [(d)] (W/m^2)
November	-13.2	19.4	0.16	13
December	-17.2	14.8	0.27	5
Annual	**-2.5**			

Notes:

[(a)] Based on synthetic estimated temperatures for Coffee Site from 1986 to 2015 from Lorax

[(b)] Based on measured data at Minto (2005-2010)

[(c)] Based on snow depth survey data at Minto (2005-2010) and mean month-end snow data at Mayo (Climate Normals 1971-2000, Environment Canada website)

[(d)] Based on measured data at Minto (2005-2010)

3.3 Soil Profile and Material Properties

There have been multiple field investigations and drilling programs undertaken by Lorax and others at the project site since 2013. Borehole MW15-01T was drilled during the March 2015 Lorax investigation and presented the most severe permafrost and ground conditions in the site area. As a result, the thermal analyses were carried out at the MW15-01T borehole location. The soil profile at MW15-01T consists of a 1.2 m layer of organics overlaying a 16.8 m ice-rich gravely sand layer and bedrock. Massive ice lenses 0.6 m, 1.3 m, and 0.6 m thick are embedded at depths of 8.8 m, 10 m, and 11.9 m below grade and within the gravely sand layer, respectively (Lorax 2016b).

The material properties used in the thermal analyses are presented in Table 2. The index soil properties were estimated from borehole logs and past experience with similar soils. The soil thermal properties were determined indirectly from well-established correlations with soil index properties (Farouki 1986; Johnston 1981).

Table 2: Material Properties Used in Thermal Analyses

Material	Water Content (%)	Bulk Density (Mg/m^3)	Thermal Conductivity (W/m-°C)		Specific Heat (kJ/kg°C)		Latent Heat (MJ/m^3)
			Frozen	Unfrozen	Frozen	Unfrozen	
Bedrock	0.5	2.66	3.0	3.0	0.74	0.75	4
Gravely sand	8	2.32	2.46	2.05	0.83	0.99	57
Ice	100	0.92	2.21	0.56	2.09	4.22	334
Peat	100	0.80	0.48	0.29	1.89	2.94	134

3.4 Applied Boundary Conditions

A ground-air boundary was applied to the surface of the soil profile to account for the influence of climate conditions on the ground surface exposed to air. A heat flux boundary was assigned at the model base in the thermal analyses to simulate the natural geothermal gradient at depths in the region. The heat flux value was calculated based on the typical thermal gradient at Coffee Creek (2.8°C/100 m) and the thermal conductivity of the bedrock.

Evapotranspiration effects were also included in the thermal analyses to account for the undisturbed layer of vegetation in the area.

3.5 Thermal Calibration Results

A thermistor cable was installed in borehole MW15-01T after drilling was completed. Initial ground temperatures at the project site were estimated by applying the mean climatic conditions described in Section 3.2 over a 40 year period, by which time, ground temperatures had stabilized and varied very little from year to year. The predicted permafrost temperature at a depth of 20 m is approximately -1.3°C, which is found within the range of typical permafrost temperatures (-2°C and -0.6°C) at the project site.

The predicted and measured temperatures were compared for several dates between April 2015 and May 2016 (Figure 1). Table 3 compares the predicted and measured ground temperatures at selected depths below the original ground surface for MW15-01T on May 12, 2016.

Table 3: Measured and Predicted Ground Temperatures at MW15-01T

Depth below Ground Surface (m)	Measured on May 12, 2016 (°C)	Predicted on May 12, 2016 (°C)
-0.5	0.1	-0.8
-2.0	-1.5	-2.7
-3.5	-2.0	-2.6
-5.0	-2.0	-2.3
-12	-1.6	-1.5
-20	-1.5	-1.3
-35	-1.0	-1.0
-50	-0.6	-0.6

The good correlation between predicted and measured temperatures in Table 3 indicates that the model and input parameters are reasonable and can be used for the long-term thermal evaluation.

4.0 THERMAL EVALUATION OF COFFEE MINE SITE STUDY AREA UNDER LONG-TERM CLIMATE CONDITIONS

4.1 Climatic Data

Mean climate conditions summarized in Section 3.2 were used in the thermal evaluation analyses.

4.2 Soil Profile and Material Properties

Soil profile and material properties summarized in Section 3.3 were used in the thermal evaluation analyses.

4.3 Climate Change Projection

Historical warming trends in annual air temperatures at the nearby weather stations (McQuesten and Pelly Ranch) were observed. It is expected that a similar warming trend may have existed in the past at the project site.

The Adaptation and Impacts Research Section (AIRS) of Environment Canada produced a report (Arctic Ensemble Scenarios) summarizing findings from the most recent climate change modelling assessment for the Arctic

(Environment Canada 2009). AIRS adopted an ensemble approach (multi-model means/medians) to reduce the uncertainty associated with any individual model. Model validation over the historical period from 1971 to 2000 was first used to identify those models which best reproduced the mean annual temperature of this period against the National Centre for environmental prediction global gridded dataset. Subsequently, only the four best agreement models were used to produce the final ensemble projections. The four best ranking models within each sector were then used as an ensemble to produce projections of temperature changes in the 2020s, 2050s, and 2080s for both the 'A1B' (middle of the road emission) and 'A2' (high emission) scenarios. The Canadian Standards Association (CSA) (2010) adopted the climate change projections in Environment Canada (2009).

The project site (62°52'N, 139°10'W) is located in the arctic zone W1 in Environment Canada (2009) and CSA (2010). The predicted mean temperature changes from the 1970 to 2000 baseline under the 'A1B' and 'A2' scenarios in Zone W1 (CSA 2010) are presented in Table 4.

Table 4: Predicted Seasonal Air Temperature Changes in Zone W1 (CSA, 2010)

Period	Predicted Seasonal Air Temperature Changes from 1971-2000 Baseline under Moderate (A1B) Green-house Gas Emission Scenario (°C)				Predicted Seasonal Air Temperature Changes from 1971-2000 Baseline under High (A2) Green-house Gas Emission Scenario (°C)			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
2011-2040	0.9	0.9	0.6	0.6	1.2	1.0	0.9	1.1
2041-2070	2.3	2.0	1.6	2.2	2.7	1.9	1.7	2.1
2070-2100	4.3	2.8	2.5	2.9	4.6	3.4	3.0	3.6

4.4 Thermal Analyses Results

A series of thermal analyses were carried out to determine the duration of thaw of the permafrost rich soils existing at the project site. The thermal analyses were conducted under both long-term mean air temperature condition (i.e., no climate change) and projected climate change scenarios.

The long-term mean air temperature condition (i.e., no climate change) will not undergo an increase in thaw depth over time as no warming effects are accounted for; the depth of thaw would remain approximately 1.2 m and would remain within the peat layer. Therefore, the permafrost soils would remain in a frozen condition.

Tables 5 and 6 present the results of the duration of thaw of the permafrost soils at the project site under the long-term A1B and A2 climate change scenarios, respectively.

Table 5: Duration of Thaw of Permafrost Soils and Ice under A1B Scenario

Material	Elevation	Time	Permafrost Condition		
			Frozen	Thawing	Thawed
Gravely sand above ice lenses	796.2 m to 803.8 m	period	Year 2017 to 2045	Year 2046 to 2098	Year 2099
		duration	28 years	52 years	-
Ice lenses with embedded gravely sand layers	792.5 m to 796.2 m	period	Year 2017 to 2084	Year 2085 to 2105	Year 2106
		duration	67 years	20 years	-

Table 5: Duration of Thaw of Permafrost Soils and Ice under A1B Scenario

Material	Elevation	Time	Permafrost Condition		
			Frozen	Thawing	Thawed
Gravely sand below ice lenses	787 m to 792.5 m	period	Year 2017 to 2084	Year 2085 to 2105	Year 2106
		duration	67 years	20 years	-

Table 6: Duration of Thaw of Permafrost Soils and Ice under A2 Scenario

Material	Elevation	Time	Permafrost Condition		
			Frozen	Thawing	Thawed
Gravely sand above ice lenses	796.2 m to 803.8 m	period	Year 2017 to 2038	Year 2039 to 2091	Year 2092
		duration	21 years	52 years	-
Ice lenses with embedded gravely sand layers	792.5 m to 796.2 m	period	Year 2017 to 2078	Year 2079 to 2099	Year 2100
		duration	61 years	20 years	-
Gravely sand below ice lenses	787 m to 792.5 m	period	Year 2017 to 2078	Year 2079 to 2099	Year 2100
		duration	61 years	20 years	-

Figures 2 and 3 present the temperature history in the middle ice lens layer (el. 793.7 m to 795 m) embedded within the gravely sand. These figures both illustrate that the duration of thaw of the massive ice lenses occurs gradually over approximately 20 years under both the A1B and A2 climate change scenarios, respectively.

5.0 CONCLUSION

The thermal analyses results indicate that the permafrost soils and the embedded massive ice lenses that exist at the project site gradually thaw over time after remaining in a frozen condition for several years. Overall:

- The permafrost soils remain in a frozen condition under the long-term mean air temperature condition (i.e., no climate change). The thaw depth is approximately 1.2 m and will remain within the top peat layer.
- The gravely sand layer located above the massive ice lenses will remain in a frozen condition for approximately 28 and 21 years under the A1B and A2 climate scenarios, respectively. This layer will then gradually thaw over the following for approximately 52 years.
- The massive ice lenses with embedded gravely sand layers will remain in a frozen condition for approximately 67 and 61 years under the A1B and A2 climate scenarios, respectively. This layer will then gradually thaw over the following for approximately 20 years.
- The gravely sand layer located below the massive ice lenses will remain in a frozen condition for approximately 67 and 61 years under the A1B and A2 climate scenarios, respectively. This layer will then gradually thaw over the following for approximately 20 years.

6.0 LIMITATIONS OF REPORT

This report and its contents are intended for the sole use of Goldcorp Inc. and their agents. Tetra Tech Canada Inc. (Tetra Tech) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than Goldcorp Inc., or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this report is subject to the terms and conditions stated in Tetra Tech's Services Agreement. Tetra Tech's General Conditions are attached to this memo.

7.0 CLOSURE

We trust this technical memo meets your present requirements. If you have any questions or comments, please contact the undersigned.

Respectfully submitted,
Tetra Tech Canada Inc.

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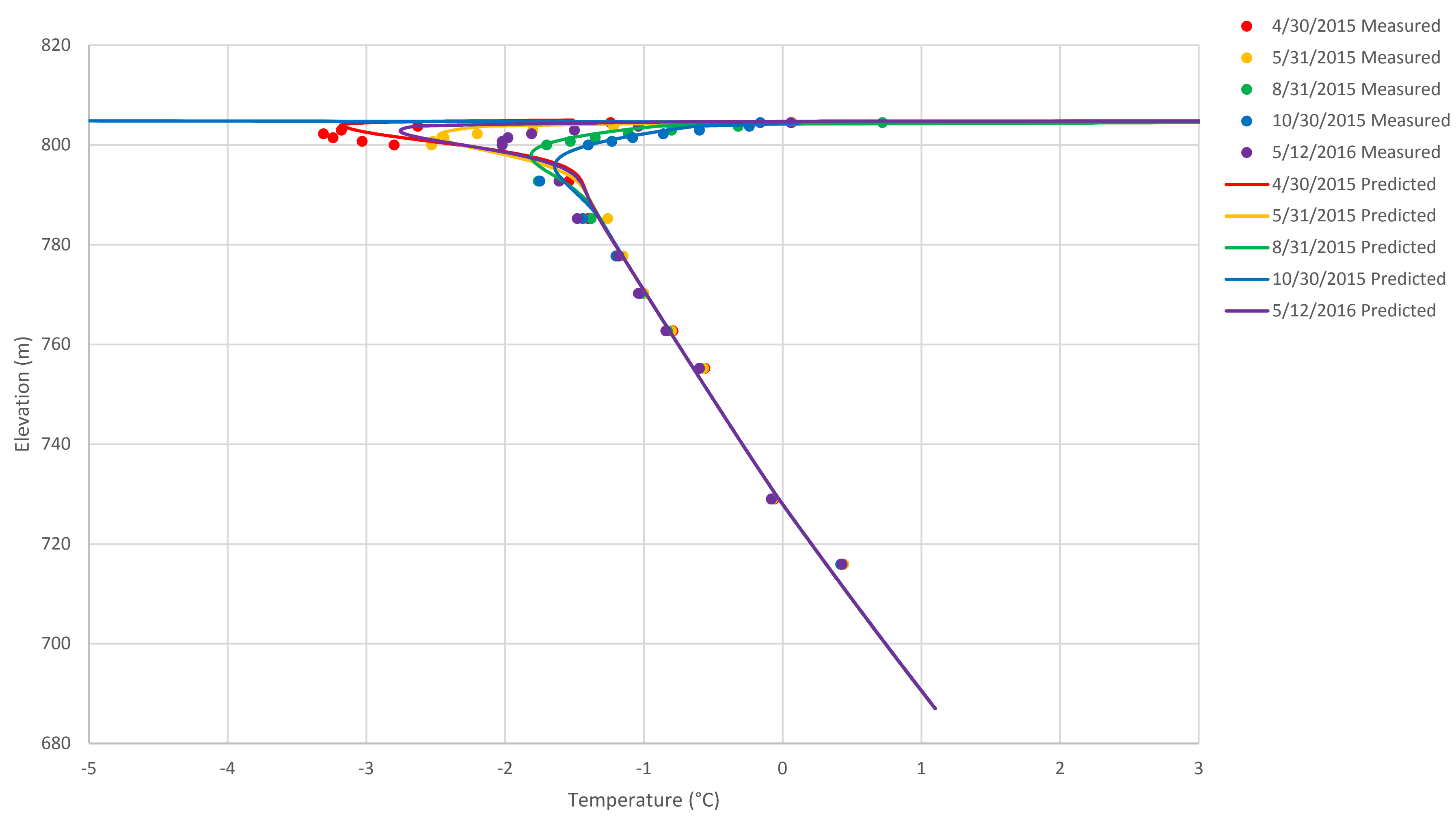
FIGURES



LEGEND

NOTES

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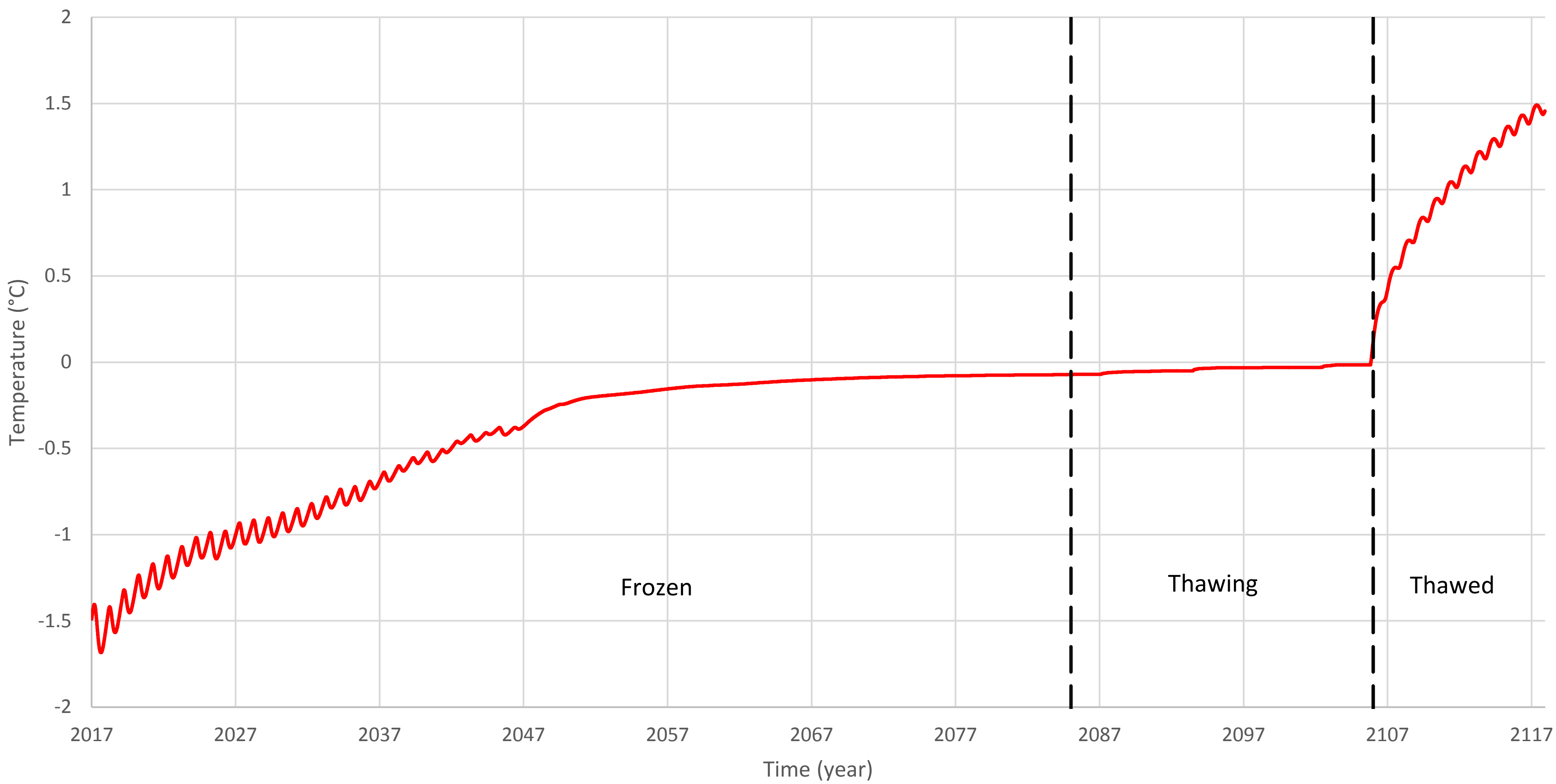
THERMAL ANALYSIS OF PERMAFROST SOILS COFFEE GOLD PROJECT, YT

Ground Temperature Calibration at Borehole MW15-01T

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03004-01	CP	HX	HX	A

OFFICE	DATE
EDM	January 2017

Figure 1



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THERMAL ANALYSIS OF PERMAFROST SOILS
COFFEE GOLD PROJECT, YT

Temperature History of the Middle Ice Lens Layer Under the A1B Climate Scenario

PROJECT NO.	DWN	CKD	APVD	REV
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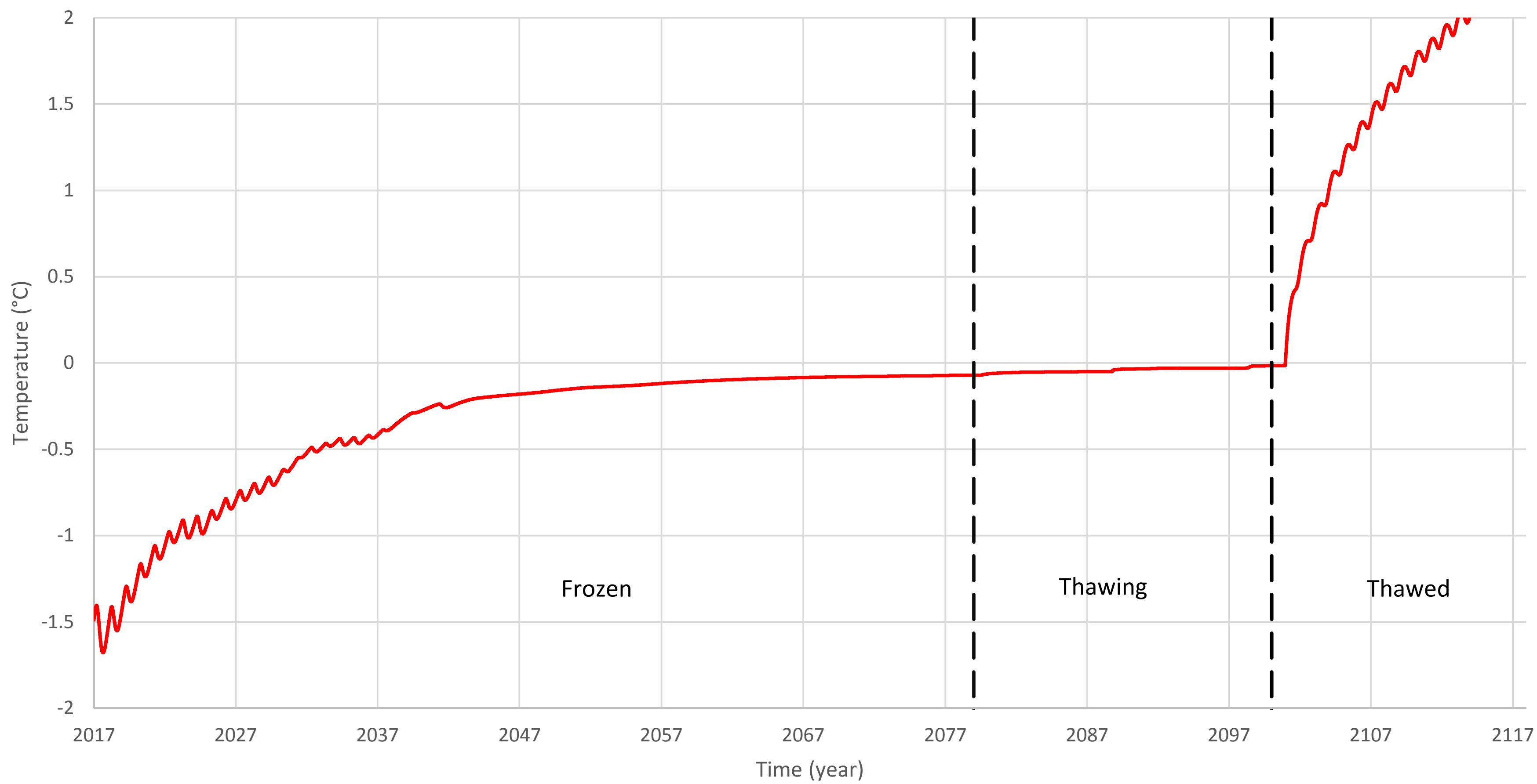
EDM	January 2017

Figure 2



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THERMAL ANALYSIS OF PERMAFROST SOILS COFFEE GOLD PROJECT, YT

Temperature History of the Middle Ice Lens Layer Under the A2 Climate Scenario

PROJECT NO.	DWN	CKD	APVD	REV
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OFFICE	DATE
EDM	January 2017

Figure 3

APPENDIX A

TETRA TECH'S GENERAL CONDITIONS

GENERAL CONDITIONS

GEOTECHNICAL REPORT

This report incorporates and is subject to these "General Conditions".

1.1 USE OF REPORT AND OWNERSHIP

This geotechnical report pertains to a specific site, a specific development and a specific scope of work. It is not applicable to any other sites nor should it be relied upon for types of development other than that to which it refers. Any variation from the site or development would necessitate a supplementary geotechnical assessment.

This report and the recommendations contained in it are intended for the sole use of TETRA TECH's Client. TETRA TECH does not accept any responsibility for the accuracy of any of the data, the analyses or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than TETRA TECH's Client unless otherwise authorized in writing by TETRA TECH. Any unauthorized use of the report is at the sole risk of the user.

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Both electronic file and hard copy versions of TETRA TECH's instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except TETRA TECH. TETRA TECH's instruments of professional service will be used only and exactly as submitted by TETRA TECH.

Electronic files submitted by TETRA TECH have been prepared and submitted using specific software and hardware systems. TETRA TECH makes no representation about the compatibility of these files with the Client's current or future software and hardware systems.

1.3 ENVIRONMENTAL AND REGULATORY ISSUES

Unless stipulated in the report, TETRA TECH has not been retained to investigate, address or consider and has not investigated, addressed or considered any environmental or regulatory issues associated with development on the subject site.

1.4 NATURE AND EXACTNESS OF SOIL AND ROCK DESCRIPTIONS

Classification and identification of soils and rocks are based upon commonly accepted systems and methods employed in professional geotechnical practice. This report contains descriptions of the systems and methods used. Where deviations from the system or method prevail, they are specifically mentioned.

Classification and identification of geological units are judgmental in nature as to both type and condition. TETRA TECH does not warrant conditions represented herein as exact, but infers accuracy only to the extent that is common in practice.

Where subsurface conditions encountered during development are different from those described in this report, qualified geotechnical personnel should revisit the site and review recommendations in light of the actual conditions encountered.

1.5 LOGS OF TESTHOLES

The testhole logs are a compilation of conditions and classification of soils and rocks as obtained from field observations and laboratory testing of selected samples. Soil and rock zones have been interpreted. Change from one geological zone to the other, indicated on the logs as a distinct line, can be, in fact, transitional. The extent of transition is interpretive. Any circumstance which requires precise definition of soil or rock zone transition elevations may require further investigation and review.

1.6 STRATIGRAPHIC AND GEOLOGICAL INFORMATION

The stratigraphic and geological information indicated on drawings contained in this report are inferred from logs of testholes and/or soil/rock exposures. Stratigraphy is known only at the locations of the testhole or exposure. Actual geology and stratigraphy between testholes and/or exposures may vary from that shown on these drawings. Natural variations in geological conditions are inherent and are a function of the historic environment. TETRA TECH does not represent the conditions illustrated as exact but recognizes that variations will exist. Where knowledge of more precise locations of geological units is necessary, additional investigation and review may be necessary.

1.7 PROTECTION OF EXPOSED GROUND

Excavation and construction operations expose geological materials to climatic elements (freeze/thaw, wet/dry) and/or mechanical disturbance which can cause severe deterioration. Unless otherwise specifically indicated in this report, the walls and floors of excavations must be protected from the elements, particularly moisture, desiccation, frost action and construction traffic.

1.8 SUPPORT OF ADJACENT GROUND AND STRUCTURES

Unless otherwise specifically advised, support of ground and structures adjacent to the anticipated construction and preservation of adjacent ground and structures from the adverse impact of construction activity is required.

1.9 INFLUENCE OF CONSTRUCTION ACTIVITY

There is a direct correlation between construction activity and structural performance of adjacent buildings and other installations. The influence of all anticipated construction activities should be considered by the contractor, owner, architect and prime engineer in consultation with a geotechnical engineer when the final design and construction techniques are known.

1.10 OBSERVATIONS DURING CONSTRUCTION

Because of the nature of geological deposits, the judgmental nature of geotechnical engineering, as well as the potential of adverse circumstances arising from construction activity, observations during site preparation, excavation and construction should be carried out by a geotechnical engineer. These observations may then serve as the basis for confirmation and/or alteration of geotechnical recommendations or design guidelines presented herein.

1.11 DRAINAGE SYSTEMS

Where temporary or permanent drainage systems are installed within or around a structure, the systems which will be installed must protect the structure from loss of ground due to internal erosion and must be designed so as to assure continued performance of the drains. Specific design detail of such systems should be developed or reviewed by the geotechnical engineer. Unless otherwise specified, it is a condition of this report that effective temporary and permanent drainage systems are required and that they must be considered in relation to project purpose and function.

1.12 BEARING CAPACITY

Design bearing capacities, loads and allowable stresses quoted in this report relate to a specific soil or rock type and condition. Construction activity and environmental circumstances can materially change the condition of soil or rock. The elevation at which a soil or rock type occurs is variable. It is a requirement of this report that structural elements be founded in and/or upon geological materials of the type and in the condition assumed. Sufficient observations should be made by qualified geotechnical personnel during construction to assure that the soil and/or rock conditions assumed in this report in fact exist at the site.

1.13 SAMPLES

TETRA TECH will retain all soil and rock samples for 30 days after this report is issued. Further storage or transfer of samples can be made at the Client's expense upon written request, otherwise samples will be discarded.

1.14 INFORMATION PROVIDED TO TETRA TECH BY OTHERS

During the performance of the work and the preparation of the report, TETRA TECH may rely on information provided by persons other than the Client. While TETRA TECH endeavours to verify the accuracy of such information when instructed to do so by the Client, TETRA TECH accepts no responsibility for the accuracy or the reliability of such information which may affect the report.