Ground temperature monitoring and permafrost distribution mapping, Coffee Mine Project, Yukon

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ABSTRACT

Tetra Tech completed several geotechnical investigation programs in support of the proposed development of the Coffee Mine Project (the Project) owned by Newmont. The Project is located in west-central Yukon, in the discontinuous permafrost zone. A key objective was to acquire permafrost data, including ground temperature and ground ice content information, that would allow design of the mine infrastructure. Tetra Tech's geotechnical investigations, completed between 2015 and 2019, consisted of coring overburden and bedrock with a helicopter-transportable diamond drill rig. Chilled drilling fluid was used to minimize thermal disturbance of permafrost and recover undisturbed frozen core samples. Twenty multi-bead ground temperature cables and numerous single-bead thermistor strings were installed in some of the 103 geotechnical boreholes completed to determine ground thermal conditions and monitor changes in permafrost temperatures. The data collected allowed for accurate mapping of permafrost distribution. The surface appearance of terrain units where permafrost conditions were confirmed was extrapolated, and slope aspect and geobotanical indicators of permafrost occurrence were also used to map permafrost extent in areas lacking boreholes. Calculations of permafrost distribution within the Project Area show that approximately 61% of the mapped area is underlain by warming, locally ice-rich permafrost. Geospatial machine-learning models were created based on terrain derivatives (slope, aspect, elevation, topographic position index, and landforms), available orthoimage information (vegetation indices), and were compared to the newly mapped permafrost distribution (about 8,000 ha) to predict presence/absence of permafrost in the larger Project Area (about 39,000 ha). The model accuracy was 58% for the broader area.

1 INTRODUCTION

The Coffee Mine Project (the Project) is an open pit and heap leach mining project owned by Newmont. The Project is situated on the divide between the headwaters of Latte Creek and Halfway Creek, located in the northern Dawson Range, in west-central Yukon, approximately 400 km northwest of Whitehorse, as shown on Figure 1.

The map of Canada-Permafrost (Heginbottom et al. 1995) shows the Project Area to be within the zone of extensive discontinuous permafrost (50% to 90% of land area underlain by permafrost).

Several geotechnical field investigation programs and desktop studies have been completed in the Project Area since 2011, as discussed in Section 1.3. Tetra Tech have been advising the owners of the Project on the permafrost-related aspects of the mine development since 2013.

1.1 Background

In addition to other environmental assessments to be completed as part of the permitting and approval process, the permafrost mapping component of the environmental work was undertaken by Tetra Tech. Geotechnical and permafrost data were acquired, including frozen and unfrozen overburden and bedrock conditions, to characterize ground conditions in support of mine infrastructure design. These investigations took place between 2013 and 2019.

The ongoing monitoring of permafrost conditions carried out by Newmont and Tetra Tech includes regular collection and analysis of ground temperatures across the Project Area. The ground temperatures and other subsurface permafrost data (ground ice content, etc.) gathered in 103 geotechnical boreholes have been used by Tetra Tech to map permafrost distribution within the Project Area.

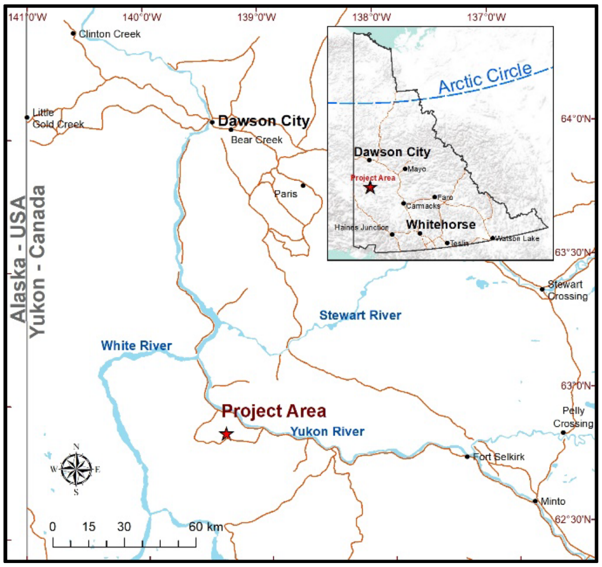

Figure 1. Project location.

https://doi.org/10.52381/ICOP2024.74.01

1.2 Rationale and Objectives

A recent increase in the intensity of mining activities in west-central Yukon generated interest in better understanding the permafrost distribution and its characteristics.

The objective of the study was to improve the assessment of the baseline permafrost conditions in the Project Area. This paper presents results of the ongoing ground temperature monitoring and permafrost distribution mapping within the Project Area. This includes an overview of the mapping methods used, as well as new methods, such as geospatial machine learning (ML) algorithms, that can be applied for more efficient permafrost distribution mapping.

1.3 Previous Studies

The most significant geotechnical investigation programs and desktop studies completed in the Project Area since 2011 include:

- Geomorphological mapping and landscape model development at the Project Area, Summer 2012 (AECOM 2012).
- Hydrogeological field investigation, Fall 2013 (Tetra Tech EBA 2014).
- Hydrogeological field investigation (Lorax 2014).
- Geotechnical field investigation, August to September 2014 (Knight Piesold 2015).
- Hydrogeological field investigation, March 2015 (Lorax 2015).
- Geotechnical field investigation with sonic drill, April 2015 (SRK 2015).
- Hydrogeological field investigation, April to June 2015 (Lorax 2015).
- Terrain stability and hazard mapping, August 2015 (PECG 2016).
- Mapping permafrost distribution along proposed Kaminak road alignment (Tetra Tech EBA 2016a).
- Environmental baseline study, the Project Area: Surficial Geology, Permafrost and Terrain Stability, 2015 to 2016 (Tetra Tech EBA 2016b).
- Mapping permafrost and related geohazards within the Project Area (Tetra Tech EBA 2016c).
- Geotechnical investigation: diamond drilling with chilled drilling fluid, Fall 2016 (Tetra Tech and SRK 2017).
- Geotechnical investigation: diamond drilling with chilled drilling fluid, Summer 2017 (Tetra Tech 2017a).
- Testpitting program, Fall 2017 (Tetra Tech 2017b).
- Geotechnical investigation: diamond drilling with chilled drilling fluid, 2018 (Tetra Tech and SRK 2019).
- Testpitting program, Fall 2018 (Tetra Tech 2019a).
- Permafrost distribution mapping update, April 2019 (Tetra Tech 2019b).
- Ground temperature monitoring update, 2022 (Tetra Tech 2023).

1.4 Physical Setting

The Project Area is located within the Klondike Plateau physiographic region. The Klondike Plateau is a Tertiary-age upland that has undergone variable uplift and stream dissection, resulting in rounded summits and ridges, and deep V-shaped valleys (Mathews 1986; Huscroft 2002). Most valley sides exhibit convex profiles, with concave profiles restricted to localized bench and gully features and valley bottoms filled with material derived from upslope erosion (PECG 2016).

The Project Area, which is situated within the Coffee Creek and Yukon River watershed, was not glaciated during the last Wisconsin glaciation (Duk-Rodkin 1999) and has since been modified by frost action and permafrost-related geomorphic processes (Tetra Tech EBA 2016b). The lack of glaciation in the Project Area means that the area has experienced a significant period of weathering. Surficial deposits consist of weathered bedrock, colluvium derived from weathered bedrock, loess, and fluvial deposits (Huscroft 2002; AECOM 2012). Colluvium is coarser grained on steeper slopes, while colluvial aprons on lower slopes commonly include ice-rich resedimented loess and peat (informally called "black muck" when intermixed; Huscroft 2002; McKenna and Lipovsky 2014). Colluvial deposits dominate high-elevation areas and upper to mid-slopes in valleys, while ice-rich "black muck" is found on lower slopes, and fluvial deposits in valley bottoms.

The climate of the Project Area is continental characterized by warm, short summers and long, cold winters. Mean annual air temperature is near -5 °C, mean January temperatures range from -23 °C to -32 °C and mean July temperatures from 10 °C to 15 °C (Yukon Ecoregions Working Group 2004). Strong thermal inversions are common from December to February in association with prolonged atmospheric stability (Williams 1995). During this period, air temperatures in valley bottoms can be tens of degrees lower than surrounding higher-elevation areas (PECG 2016). Mean annual precipitation ranges from about 300 mm to 500 mm, giving the region a semi-arid classification. The wettest period occurs in summer, when most precipitation falls as rain during rain showers and thunderstorms (Yukon Ecoregions Working Group 2004).

The Project Area comprises ecosystems ranging from boreal forests and wetlands in valleys to alpine tundra on ridge crests. Below treeline, black spruce and white spruce dominate the ecoregion in both pure stands and mixed stands that include various deciduous species, such as trembling aspen and Alaska birch (Yukon Ecoregions Working Group 2004).

2 Methodology

Tetra Tech has been studying and mapping permafrost within the Project Area since 2013. The main objective was to provide accurate characterization of the spatial variability of permafrost conditions, such as permafrost distribution, ground temperatures, volumetric ice contents, and thickness of the permafrost interval.

2.1 Geotechnical Investigations in Permafrost

Accurate mapping of spatial variability of permafrost conditions was achieved through analyses of the high-quality data collected by coring permafrost with chilled (refrigerated) drilling fluids to minimize thermal disturbance of frozen ground containing ground ice. Drilling was performed using a helicopter-portable D-10 Duralite 500 diamond drill rig with a triple tube coring system. The drilling fluid was chilled to a temperature of approximately -6 °C to -7 °C. This chilled fluid allowed the recovery of undisturbed frozen core samples and accurate estimation of volumetric ice content (% by volume of visible ice) in ice-rich permafrost. To assist with visual assessments, field "beaker" testing (Kokelj and Burn 2005) was performed on each recovered ice-rich frozen core sample to improve the accuracy of the volumetric ice content determination.

Tetra Tech reviewed deep borehole data collected by Lorax during several hydrogeological field investigations (Lorax 2016) to analyze the thickness of the permafrost interval throughout the Project Area. Permafrost depths were also determined from three ground temperature profiles plotted with ground temperature data collected in the 2018 boreholes (SRK-AP-18-06, -07, and -08) completed in the Halfway Creek valley (Tetra Tech and SRK 2019).

In total, 103 geotechnical boreholes were drilled within the Project Area.

2.2 Ground Temperature Monitoring

Completed boreholes were instrumented with single-bead thermistor strings (SBTSs) and multi-bead ground temperature cables (GTCs) to confirm the presence (or the absence) of permafrost and monitor in situ ground temperatures. SBTSs were installed to a depth of at least 6 m below the ground surface (usually between 6 m and 10 m), such that a thermistor bead would be located below the base of the active layer.

Twenty multi-bead GTCs and numerous SBTSs were installed in selected geotechnical boreholes to determine ground thermal conditions and to monitor changes in permafrost temperatures. Subsurface conditions observed in 57 testpits from Tetra Tech's 2017 program (Tetra Tech 2017b) and in 69 testpits from Tetra Tech's 2018 program (Tetra Tech 2019a) were also used to refine the permafrost mapping of the Project Area.

2.3 Air Photo Interpretation

Digital colour air photos covering the Project Area were acquired at a nominal scale of 1:20,000. These were used to generate three-dimensional (3D) digital models. Permafrost distribution mapping was initially carried out by Tetra Tech at 1:20,000 scale, based on stereoscopic interpretation of the colour air photos. The initial mapping linework was then refined in early 2016 using the 3D visualization PurVIEW system at 1:5,000 to 1:25,000 scale, the latter being a smaller scale than the nominal 1:20,000. The refined map was presented to Kaminak, the Project's previous owner, at a scale of 1:20,000 in a Technical Memo (Tetra Tech EBA 2016c), and the map has been updated since then.

Permafrost and permafrost-free polygons were delineated according to:

Geobotanical indicators:

- Stunted black spruce stands ("drunken forest") with thick moss cover (reliable indicators of shallow ice-rich permafrost),
- Deciduous (dominantly trembling aspen and / or Alaska birch) dense stands – suggesting predominantly permafrost-free terrain, and
- Mixed stands of Alaska birch (with or without aspen) and spruce (black and white) – commonly indicating permafrost-free terrain. However, mixed stands are not reliable predictors of permafrost presence or absence (McKillop et al. 2013).

Slope aspect:

- North-facing slopes indicate permafrost terrain; whereas,
- South-facing slopes suggest predominantly permafrost-free terrain.

Ground surface appearance:

- Texture, colour, hue, etc.) of those terrain units, where permafrost presence was confirmed by ground temperature measurements), was extrapolated to areas where no ground temperature instrumentation has been installed, thus allowing delineation of permafrost polygons.

ArcGIS technology was used to calculate percentages of delineated permafrost terrain units (map polygons) within the Project Area. Map polygon areas were determined within ArcGIS, followed by an export of the data to Microsoft Excel where totals and percentages were refined. The results are presented in Section 3.2.

2.4 Machine Learning (ML) Modeling

Several studies have used ML methods for high-resolution digital mapping in permafrost terrain (e.g., Siewert (2018) for soil organic carbon), but relatively few have focused on permafrost distribution. Predictive models for permafrost distribution in the Project Area were created using the mapped permafrost polygons as training data and associating spatio-statistical relationships with other available data that include LiDAR terrain derivatives (aspect, slope, landform, etc.) and imagery. The annual permafrost mapping update was input to create algorithms incorporating other key permafrost indicators based on the terrain and vegetation parameters using ML.

The permafrost distribution modeling outputs are produced at 1 m raster resolution, corresponding to the LiDAR terrain derivatives. The borehole and ground temperature data were not used as an input in the ML model. The data required 3D interpolation and complex processes that can be included in the next phase of a more detailed model. Similarly, due to the lack of high-resolution multispectral data for the site, vegetation species composition and tree height parameters were not incorporated into the model. As an alternative, a 10 m resolution Normalized Difference Vegetation Index (NDVI) and a Normalized Difference Water Index (NDWI) were calculated from Sentinel-2 data (Copernicus Sentinel data 2021-07-12 retrieved from Copernicus Open Access Hub, processed by European Space Agency).

Geospatial ML models were based on NDVI, NDWI, slope, aspect, landform, and elevation data. These factors and the classes represented are shown in Figure 2.

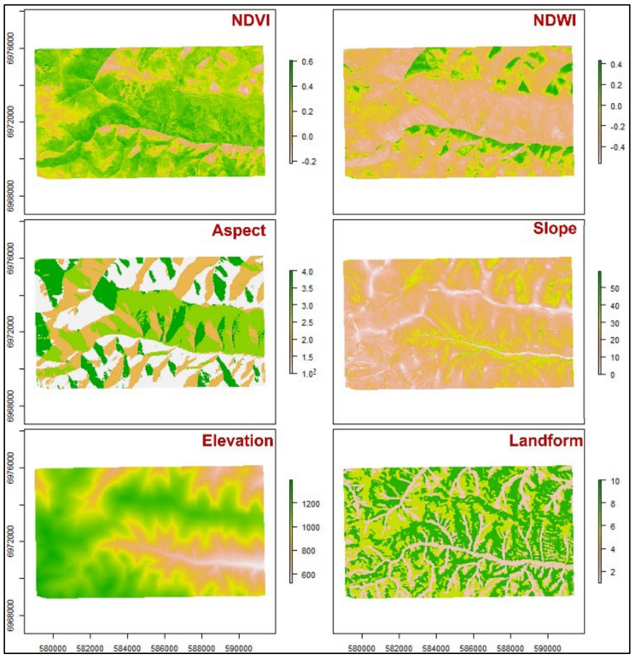

Figure 2. Factors used for ML model.

3 RESULTS

3.1 Ground Temperature Monitoring

The GTC installed in Borehole GT17-39T at the bottom of the Halfway Creek valley (Figure 3) has shown a significant increase in ground temperature of approximately 1.7 °C from 2019 to 2022 within the 12 m to 13 m depth interval; however, the same GTC later showed an approximate 0.7 °C decrease in ground temperatures from 2022 to 2023 (Figure 4). Increasing ground temperatures have resulted in an increase in the active layer thickness by approximately 0.4 m since monitoring began in the Project Area in 2017. The active layer at this location consists of a layer of peat 200 mm thick underlain by silt with some organics approximately 0.5 m thick. The silt layer is underlain by sandy gravel. The thickness of the active layer increased from approximately 0.8 m in 2018 to approximately 1.2 m in 2022 (Figure 4). The thickness of the permafrost interval at this location has slightly decreased, by approximately 0.5 m from 2017, with the permafrost base currently located at a depth of approximately 5 m below the ground surface (Figure 4).

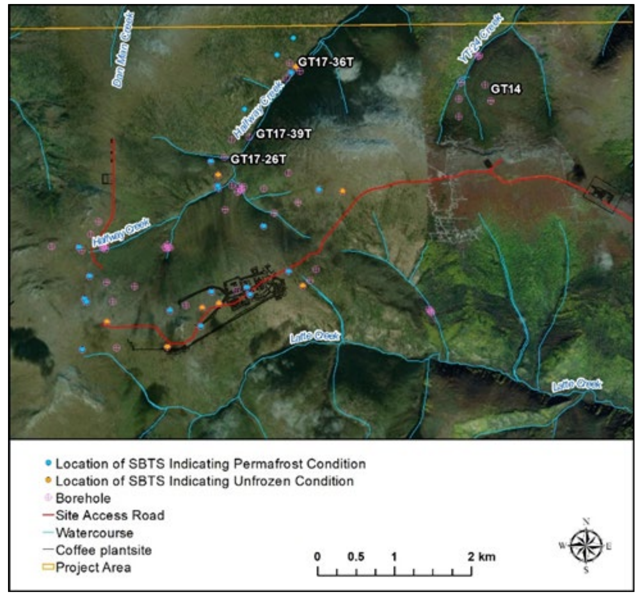

Figure 3. Coffee Mine Project Area with proposed plant site and selected borehole locations.

Temperature trends since 2016 showing ground warming were observed in 11 of the 20 instrumented boreholes in the Project Area. For Borehole GT-14, located on a northwest-facing slope covered at this borehole location by a layer of intermixed silt and organic material approximately 250 mm thick underlain by sandy gravel (Figure 3), warming of permafrost of almost 0.2 °C has occurred since 2019 (Figures 5 and 6). The active layer thickness at GT-14 has increased since measurements began in 2016, from approximately 1.5 m in 2016 to 2.5 m in 2019 and 3.75 m in 2023 (Figure 5).

The lowest permafrost temperatures (-2.1 °C) in the Project Area were measured at Borehole GT17-36T on a north-facing slope of the Halfway Creek valley (Figure 3) at a depth between 17 m and 20 m below ground surface (Figure 7). The active layer thickness (approximately 3.0 m) at this location has remained unchanged since monitoring began in 2017 (Figure 7).

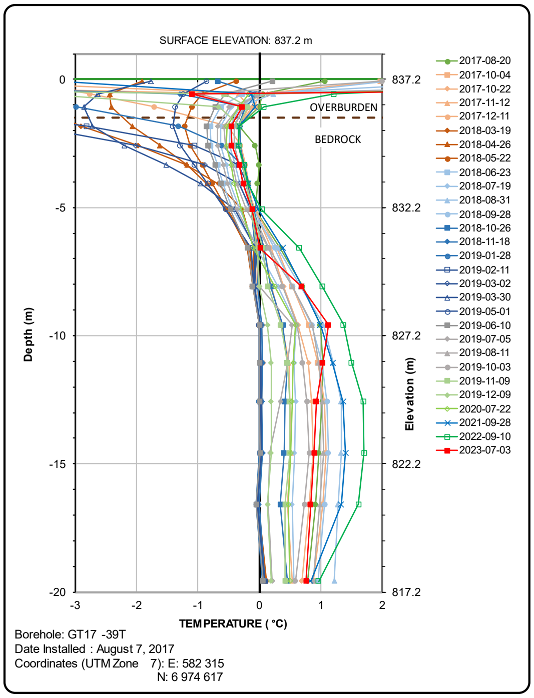

Figure 4. Ground temperature profile at Borehole GT17-39T showing a warming trend (Bottom of Halfway Creek Valley).

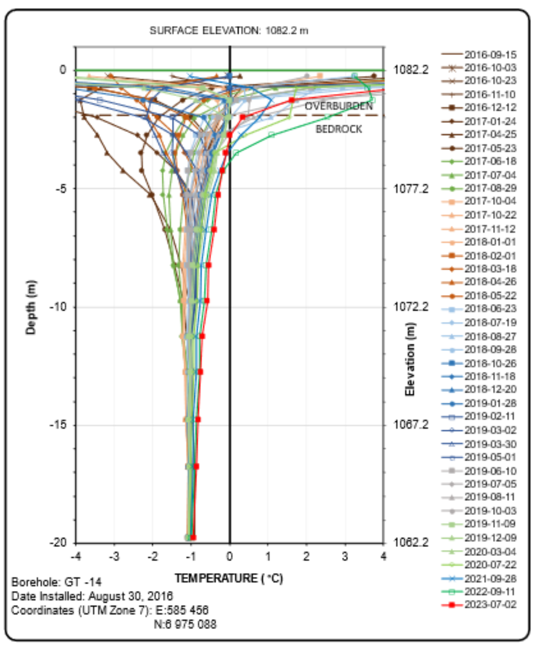

Figure 5. Ground temperature profile at Borehole GT-14 showing slight warming trend (a northwest-facing slope).

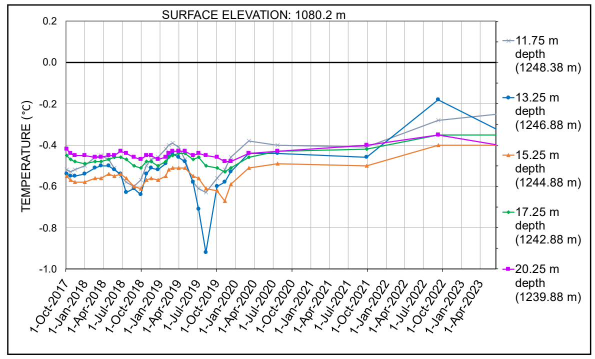

Figure 6. Ground temperature profile at Borehole GT-14 showing increase in permafrost temperatures from 11.75 m to 20.25 m depth below ground surface between 2017 and 2023 (north-facing slope of Halfway Creek).

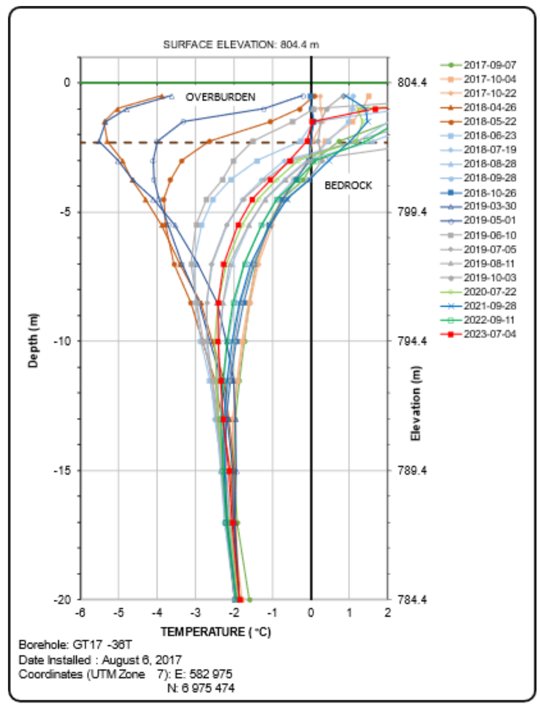

Figure 7. Ground temperature profile at Borehole GT17-36T showing lowest permafrost temperatures (a north-facing slope of Halfway Creek).

Four other GTCs have shown very slight cooling trends since 2017. The largest temperature decrease, up to approximately 0.2 °C from 2022 to 2023, occurred in an area of unstable permafrost temperatures, i.e., very warm permafrost (close to 0 °C) located at an east to northeast-facing slope of an unnamed creek tributary of Halfway Creek (Borehole GT17-26T; Figure 3). The remaining GTCs show no apparent changes in ground temperatures since 2017.

3.2 Permafrost Distribution Mapping

The initial map of the spatial distribution of permafrost in the Project Area (Tetra Tech EBA 2016c) was updated (Tetra Tech 2019b, 2023a, 2023b), as new permafrost data became available. The latest mapping update, completed in July 2023, is shown in Figure 8.

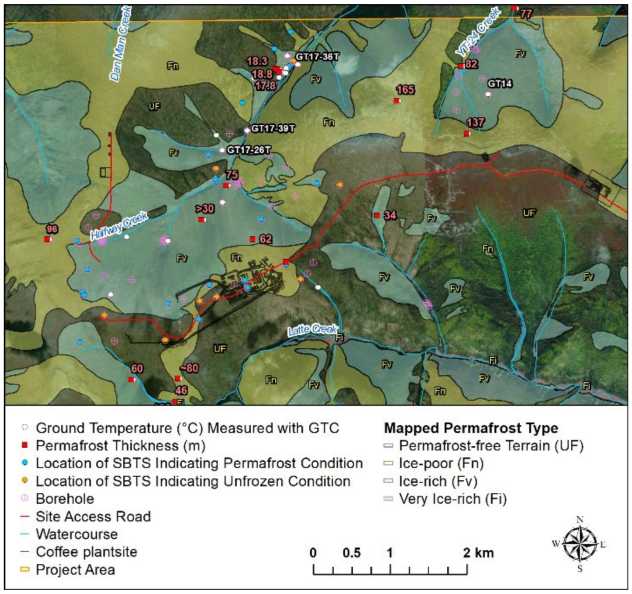

Figure 8. Permafrost distribution and thickness in the project area.

Permafrost distribution within the Project Area was divided into four terrain units (shown on Figure 8):

- Predominantly very ice-rich permafrost – ground ice content exceeding 50% by volume of visible ice (ICE and SOIL) – labeled as "**Fi**" on the map;
- Predominantly ice-rich permafrost – ground ice contents ranging between 10% and 50% by volume of visible ice – labeled as "**Fv**" on the map;
- Predominantly ice-poor permafrost – ground ice content generally less than 10% by volume of visible ice or non-visible ground ice – labeled as "**Fn**" on the map; and
- Areas confirmed by SBTSs and GTCs to be mainly permafrost-free – labelled as "**UF**" on the map and shown as transparent (not coloured) polygons. These areas may contain patches of permafrost where ground conditions are favourable, such as localized shallow low-lying areas with patches of peat or organic-enriched soil.

Tetra Tech's calculations of permafrost distribution, i.e., percentages of delineated permafrost terrain units (map polygons) show that approximately 61% of the Project Area is underlain by permafrost. This result agrees with the Canada-Permafrost map (Heginbottom et al. 1995), which shows the Project located within the zone of extensive discontinuous permafrost (50% to 90% of land area is underlain by permafrost).

The permafrost distribution within the Project Area was further broken down, as follows:

- 0.5% of the area is underlain by very ice-rich permafrost (**Fi**);
- 31% of the area is underlain by predominantly ice-rich permafrost (**Fv**);
- 29.5% of the area is underlain by predominantly ice-poor permafrost (**Fn**), and
- 39% of the Project Area is expected to be permafrost-free (**UF**).

Review of the deep borehole data collected by Lorax (Lorax 2016) shows that the thickest permafrost interval (165 m) measured to date within the Project Area underlies a north-facing slope of the divide between the Halfway Creek and the YT-24 Creek (Figure 8).

3.3 Machine Learning Modeling

The output from the ML model is presented in Figure 9. The model provided the ability to map permafrost at a 1-m resolution which can easily be overlooked by the human eye. An additional advantage of the ML model was to extend the permafrost mapping to areas that were not mapped initially. Permafrost presence-absence model output using just these two classes of permafrost distribution showed higher accuracies (58%) compared to the test data that is based on the manual permafrost distribution mapping (Section 3.2), but the accuracies of individual classes of permafrost distribution (ice-poor **Fn**, ice-rich **Fv** and very ice-rich **Fi**) were lower (42%) than the permafrost presence-absence model outputs.

4 DISCUSSION

Permafrost distribution is difficult to identify directly on a large scale. The 3D mapping used in this study, coupled with ground temperature monitoring, is the most accurate method for completing this type of work, but it is time-consuming and requires expertise in vegetation identification and knowledge of permafrost derivative parameters (slope, aspect, landform, etc.). Landscape indicators combined with terrain data, multispectral remote sensing data, and other GIS tools can be used in combination with the existing mapping done to take advantage of ML on a large scale.

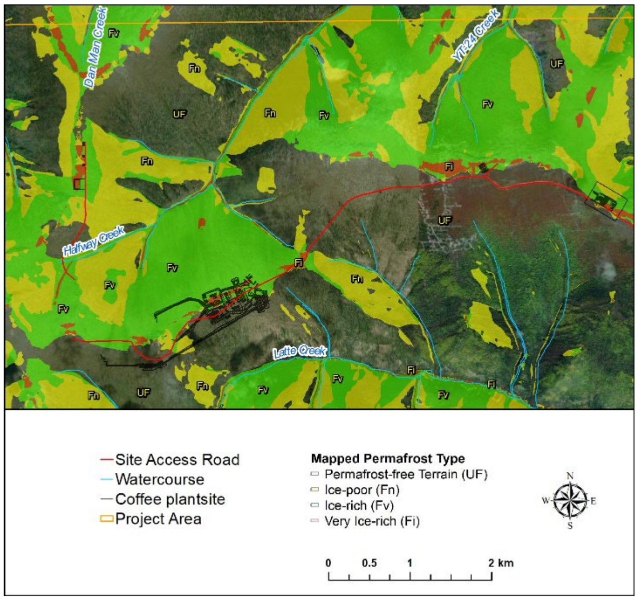

Figure 9. ML model output for same classes as that of the training data (permafrost-free, ice-poor, ice-rich, and very ice-rich).

The preliminary results achieved using the available data for the current ML model are promising. The model outputs could have been further improved with the inclusion of key landscape variables such as species composition and tree height. Both parameters could be acquired while utilizing available remote sensing techniques and models like Random Forest on multi-temporal high-resolution multi-spectral data. Further work will benefit greatly from the inclusion of these types of data.

ML models allow for efficient, high-resolution permafrost distribution mapping. Such models can be created and improved on a regional scale. Model outputs can be created for areas where data is available and checked/ corrected from local knowledge, borehole, and ground temperature data. The time required to make the checks and corrections will be significantly less than on-screen digitizing of a large area.

Permafrost distribution mapping is a specialized field with a handful of experts in the world. Permafrost distribution mapping on a fine scale is done manually based on field observations/data and experience. Capturing expert knowledge (to train data) and empirical data to produce relationships between key indicators and spatial variables can be accomplished using Bayesian networks (BN; Iqbal and MacLean 2010). BN, together with ML, is an avenue to be further explored for more efficient, high-resolution, large-scale mapping.

The use of SBTSs in completed boreholes is a simple, proven, useful, and cost-effective method to confirm the presence (or the absence) of permafrost at specific locations and depths within the discontinuous permafrost zone. The ground temperature data collected with SBTSs can be efficiently used for permafrost distribution mapping. SBTSs should be installed to a depth of at least 6 m below the ground surface (usually between 6 m and 10 m) to ensure the thermistor bead is located within permafrost, if present, i.e., below the base of the active layer. The use of SBTSs should be incorporated in every geotechnical drilling plan in the discontinuous permafrost zone, ideally with a SBTS installed in every borehole without a GTC.

5 Conclusions

Although the monitoring period of ground temperatures and permafrost extent in the Project Area is relatively short (seven years), the data collected allows improved assessment of baseline permafrost conditions, informs impact assessment, and facilitates identification of project effects.

The permafrost data collected and analyzed by Tetra Tech allowed for accurate mapping of permafrost distribution, showing that approximately 61% of the Project Area is underlain by warm, locally ice-rich, permafrost up to 165 m thick, with permafrost temperatures ranging from 0.0 °C to -2.1 °C at the depth of zero annual amplitude (between 15 m and 20 m).

The mapping process has been time-consuming, involving on-screen digitization using 3D visualisation software (PurVIEW). The ML model utilizing the terrain-derived outputs and training data from the manual permafrost mapping shows promising preliminary results. Model accuracy for the broader permafrost presence-absence map option, compared to the 8,000 ha already mapped was 58%. Further work will include additional data inputs to the model: multispectral data, vegetation species composition, and tree heights. This is expected to improve model accuracy. Regional scale ML models are also scheduled to be completed.

6 Acknowledgements

This paper is published with the approval of Newmont.

The authors are grateful for the interest and support for the permafrost studies at the Coffee Mine Project by the Project's previous owners (Kaminak and Goldcorp), the current owner (Newmont), and their colleagues at Tetra Tech, particularly Christian Roldan, James Scott, and Kevin Jones.

The authors are thankful for the thorough review of the draft paper and the comments provided by Rita Kors-Olthof and Dr. Hongwei Xia. Final review and formatting of the paper was completed by Jen Forbes.

The constructive comments received from both anonymous reviewers are gratefully acknowledged.

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