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Investigating for dry stack tailings facility closure: multidisciplinary evaluation at the Pogo Mine, Alaska

D.P. Neuffer *SRK Consulting (US) Inc., USA*

C.W. Stevens *SRK Consulting (US) Inc., USA*

R. Staines *SRK Consulting (Australasia) Pty Ltd, Australia*

M. Umedera *Sumitomo Metal Mining Pogo LLC, USA*

S.S. McLeod *Sumitomo Metal Mining Pogo LLC, USA*

Abstract

Sumitomo Metal Mining Pogo LLC (Pogo) is the operator of the Pogo underground gold mine, located near Delta Junction, Alaska. The mine has been in operation since 2006 and produces between 380,000 and 400,000 ounces of gold annually. Filtered tailings from the flotation circuit and waste rock from the mine are placed in the dry stack tailings facility (DSTF). Expansion of the DSTF from 7 M to 18 M t has prompted further evaluation of the facility for closure planning. This paper presents data from several components of a multidisciplinary DSTF closure study, including geotechnical and geochemical test results, in situ temperature and pore pressure measurements, and estimated freezing characteristics of tailings samples.

Results of this study indicate the DSTF is physically stable and is comprised of materials that are not potentially acid-generating; these findings support operational material placement practices and elements of the DSTF closure plan. Geotechnical field and laboratory testing indicate that effective friction angles and dry densities of in situ DSTF materials are consistent with previous slope stability analyses. Geotechnical borehole drilling, thermal monitoring, and analysis indicate the presence of permafrost within the DSTF. Pore pressure measurements and drilling observations indicate a phreatic surface near the base of the DSTF. This study narrows the focus of data collection for future closure planning and provides an example of physical and chemical conditions within a dry stack tailings facility in a continental, subarctic climate. These findings are pertinent for planning, design, permitting, operation, and closure of dry stacks in similar climates.

1 Introduction

The Pogo Mine is an underground gold mine operated by Sumitomo Metal Mining Pogo LLC (Pogo), located approximately 60 km northeast of Delta Junction, Alaska (Figure 1 inset). Ore is processed by multiple milling methods including gravity, flotation, and carbon in pulp. Tailings from the flotation circuit are filtered to reduce moisture content and trucked to the dry stack tailings facility (DSTF), which fills a portion of the Upper Liese Creek valley (Figure 1), for storage. Waste rock is segregated into mineralised or nonmineralised portions by individual blasted rounds, based on the assay of grab samples. Mineralised waste rock is placed in the DSTF for geochemical segregation, and nonmineralised waste rock is used for construction of various components of the DSTF, including surface armouring on the shells and the flow-through drain. Both tailings and waste rock are placed and compacted by established method specifications based on field compaction tests (Sumitomo Metal Mining Pogo LLC, 2012a).

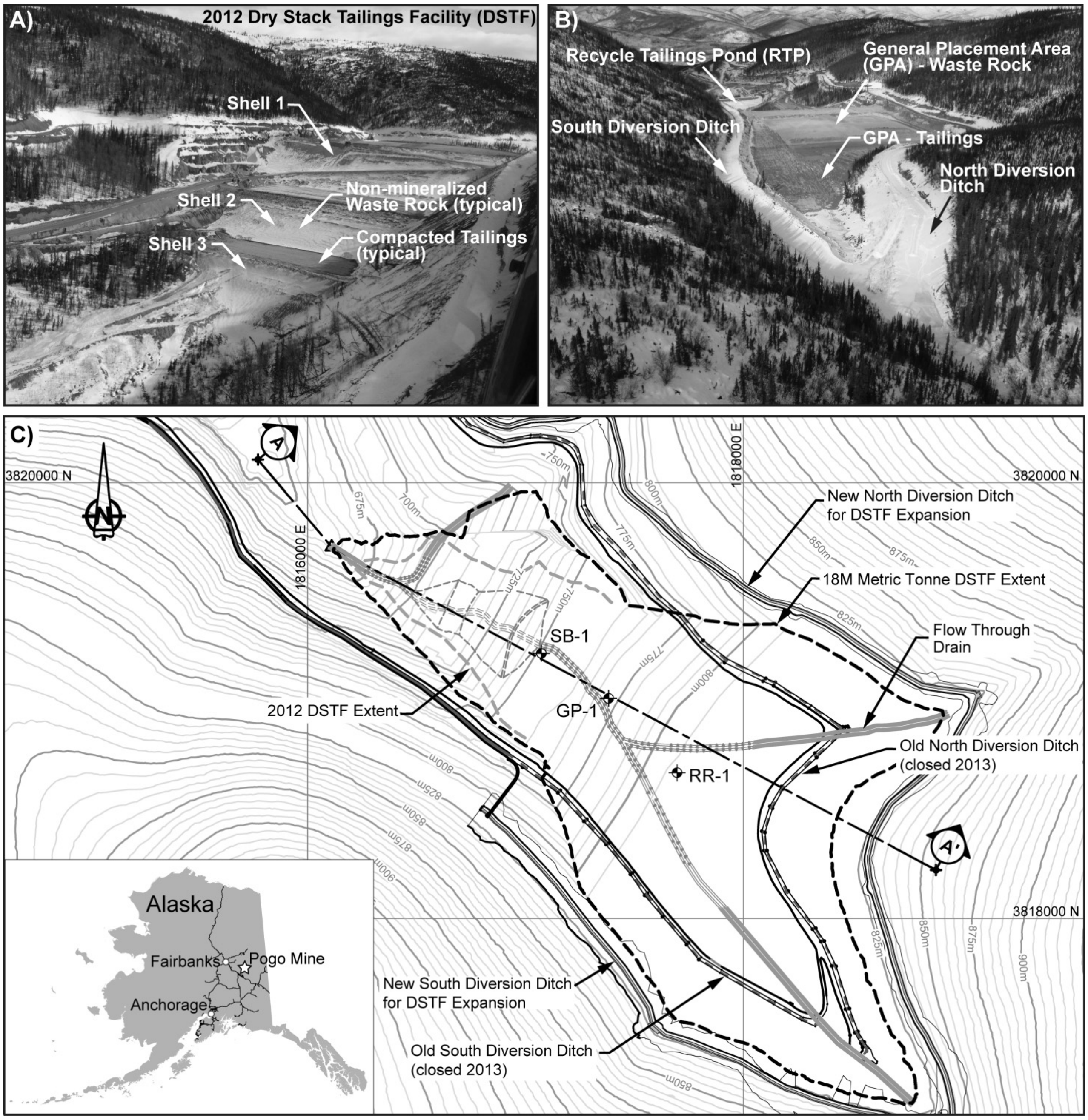

Figure 1 Oblique air photo taken of the 2012 DSTF at Pogo Mine, Alaska: a) DSTF toe and composite shells, view facing up valley to east; b) general placement area, view facing down valley to west; c) plan view of DSTF

The DSTF has been in operation since February 2006, with placement of approximately 5.3 M t of tailings and waste rock through 2011 (Sumitomo Metal Mining Pogo LLC, 2012a). The facility was originally designed by AMEC Earth and Environmental (AMEC, 2004), with a capacity of approximately 6.8 M t. In 2011, SRK Consulting Inc. updated the DSTF material balance and confirmed the need for expansion of the facility by 2013. In 2012, the Alaska Department of Natural Resources (ADNR) and Alaska Department of Environmental Conservation (ADEC) approved Pogo's plan to increase the permitted storage capacity of the DSTF from 6.8 to 18 M t; Pogo completed expansion of the surface water diversion ditches and haul road for the 18 M t facility in 2013.

Figure 2 shows a longitudinal cross-section of the 18 M t DSTF configuration. The 2012 DSTF surface is also shown. Major components of the facility include the starter and toe berms, shells, general placement area (GPA), and flow-through drain (see also Figure 1). The majority of the dry stack tailings are spread and compacted within the GPA. Mineralised and nonmineralised waste rock is placed in the GPA, where the rock is separated laterally from native ground and vertically from other lifts of waste rock by compacted tailings (Sumitomo Metal Mining Pogo LLC, 2012a). The shell adjacent to the GPA, Shell 1, is constructed of nonmineralised waste rock. Shells 2 and 3 are composite shells constructed of compacted tailings with nonmineralised waste rock on the outside portion of each shell.

Surface runoff from up-gradient of the DSTF is diverted around the facility by the north and south diversion ditches (see Figures 1B and 1C). The DSTF also includes a flow-through drain along the Liese Creek thalweg; the flow-through drain was designed to convey surface water runoff below the DSTF (AMEC, 2004). Water exiting the flow-through drain and runoff from the DSTF are collected in the recycle tailings pond (RTP) for use in mining or milling processes or for treatment and discharge.

The DSTF reclamation and closure plan (Sumitomo Metal Mining Pogo LLC, 2012b) outlines the following closure actions to be performed during operation and upon eventual completion of mining and milling:

1. Construct the DSTF with slope angles of 3H:1V during operation for physical stability during operation and closure.
2. Place GPA materials at a 2% slope to the DSTF perimeter during operation to promote drainage during operation and closure.
3. Construct armoured perimeter channels during closure to route surface water off of the DSTF and minimise erosion.
4. Place a soil cover consisting of growth media, granular soil, and nonmineralised waste rock during closure to promote revegetation and minimise erosion.

As a stipulation of the ADNR approval of the DSTF expansion, Pogo has undertaken a multidisciplinary closure study of the DSTF to "*evaluate the hydrological, geochemical, and geotechnical characteristics of the facility and proposed cover design*" and to "*model impacts to post-closure down-gradient water quality*" (ADNR, 2012). This paper presents a portion of this study related to geotechnical, thermal, hydrogeological, and geochemical characteristics of the facility. Specifically, this paper summarises methods and results of field investigations of the DSTF for geotechnical properties, pore pressures and temperatures, and geochemical characteristics. This paper further discusses the implications of these findings in the context of closure planning for the DSTF.

2 Subsurface investigation

In October of 2012, a subsurface investigation of the DSTF was performed to evaluate the geotechnical, thermal, hydrogeological, and geochemical characteristics of the facility. Three sonic boreholes (SB-1, GP-1, and RR-1) (see Figures 1 and 2 and Table 1) were vertically drilled in the following locations:

1. immediately up-gradient of the starter berm (SB-1);
2. in a portion of the GPA where tailings was expected to comprise a significant fraction of the stratigraphy (GP-1); and
3. in a portion of the GPA where mineralised red rock was expected to comprise a significant portion of the stratigraphy (RR-1).

The total drilled depth for the three holes was 107 m. These three locations were chosen to provide data from representative regions of the DSTF on a material, spatial, and temporal basis. To avoid potential effects on the DSTF flow-through drain, all three boreholes were terminated short of the depth of the flow-through drain and underlying native ground.

2.1 Geotechnical sampling and laboratory testing

Geotechnical sampling and testing were performed to provide material parameters for the DSTF slope stability analysis and closure cover evaluation. Sonic core, standard penetration testing (SPT), and Shelby tube samples were collected during the subsurface investigation. Core was recovered using a 10 cm diameter sonic coring barrel. Standard penetration test (SPT) blow counts were measured at approximate intervals of 3 m using a 136 kg hammer and a modified California sampler. Shelby tube samples were collected where stratigraphy allowed.

A total of four Shelby tube, 38 modified California, and 49 geotechnical grab samples were collected during the subsurface investigation. Laboratory testing performed on select samples included analyses for grain size, Atterberg limits, natural moisture and density, consolidated-undrained triaxial shear with pore pressure measurements, flexible wall permeability, and consolidation.

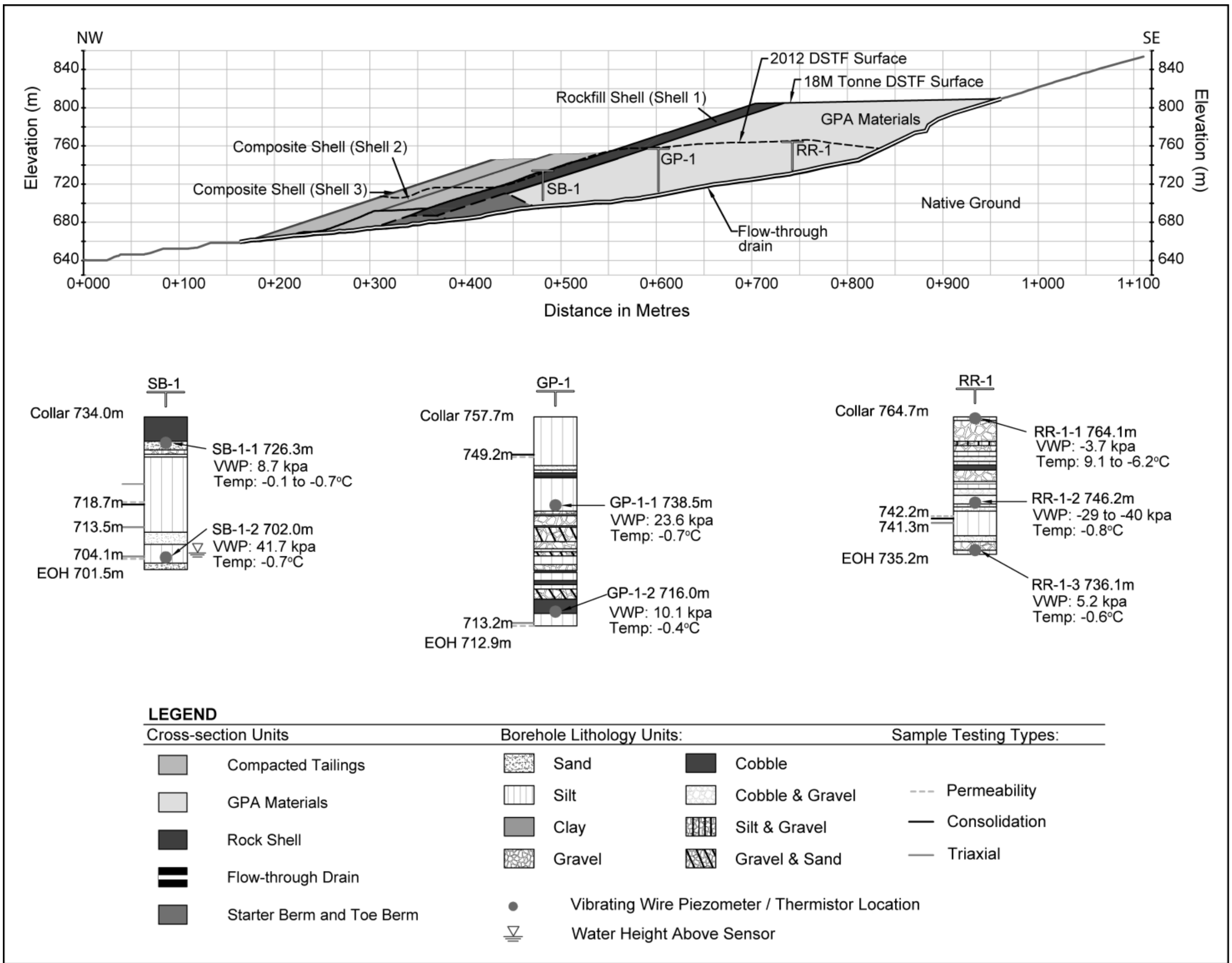

Figure 2 Cross-section of 18 M t DSTF and generalised borehole stratigraphy at SB-1, GP-1, and RR-1 (for clarity, the stratigraphic locations of SPT and geotechnical grab samples are not shown)

2.2 Borehole instrumentation

RST vibrating wire piezometers (VWP) were installed in each of the three boreholes to determine the presence and extent of saturated zones within the DSTF and to monitor changes in pore pressure. DSTF temperatures were also measured using thermistors located within each VWP sensor. The installation depth of each sensor is presented in Table 1. The installation depth of each sensor was based on borehole stratigraphy and depth; for instance, interfaces where higher permeability waste rock overlaid lower permeability tailings were targeted for sensor placement. Over time, sensor depth is expected to increase as tailings and waste rock are added to the DSTF.

The seven VWPs with integral thermistors were installed shortly after drilling was complete. Sensors were attached to a 2.5 cm diameter PVC guide tube and lowered into the hole through the drill rods to ensure borehole stability and proper installation depth. Instrumented intervals of the boreholes were backfilled with cement-bentonite grout, based on methods outlined by Mikkelson and Green (2003).

Field calibration and initial readings were taken at the surface prior to installation, after installation in the open borehole, and after backfilling with grout, using procedures outlined by RST (2012). The measured vibrating wire frequency was converted to pressure following conversion equations prescribed by RST (2012). The VWP data were also corrected for changes in surface barometric pressure. The accuracy of the VWP pressure sensors are considered to be ± 0.7 kPa (equivalent to 0.1 m of water) (RST, 2012). Temperature thermistors are accurate to ±0.2°C (RST, 2012). Data loggers with a 6 hour sampling interval were connected to the VWP and integral thermistors.

Table 1 Dry stack tailings facility borehole and instrument sensor details

Drill borehole	Location description	Drill depth (m)	Sensor ID	Sensor description	Sensor depth[1] (m b.g.s.)	Sensor elevation[2] (m a.m.s.l.)
SB-1	Starter berm	32.5	VW22850	Shallow	7.6	726.3
			VW22851	Deep	31.9	702.0
GP-1	General placement area	44.8	VW22852	Shallow	19.2	738.5
			VW22853	Deep	41.8	716.0
RR-1	Red rock area	29.5	VW23152	Shallow	0.6	764.1
			VW22854	Mid	18.6	746.2
			VW22855	Deep	28.7	736.1

1. Sensor depth is based on the depth below ground surface (b.g.s.) at the time of sensor installation (October 2012).
2. Elevations are presented as metres above mean sea level (m a.m.s.l.).

3 Borehole stratigraphy and geotechnical properties

The generalised borehole stratigraphy encountered in SB-1, GP-1, and RR-1 is shown in Figure 2. The generalised borehole stratigraphy encountered at SB-1, GP-1, and RR-1 was characterised by silt-size tailings interlayered with waste rock consisting of sand and gravel, gravel, and cobbles. The vertical sequence of material encountered by each borehole is spatially variable due to the placement of tailings and waste rock.

At borehole SB-1, the uppermost units consisted of cobbles, sand, and gravel, which make up Shell 1. Shell 1 was underlain by silt-size tailings interlayered with sand, forming the toe of the general placement area (GPA) (Figure 2). Boreholes GP-1 and RR-1 were located within the GPA up-gradient of borehole SB-1. The stratigraphy at borehole GP-1 was characterised by interlayered silt-size tailings and coarse-grained waste rock. Borehole stratigraphy at RR-1 was predominately coarse-grained waste rock interlayered with thinner units of silt-size tailings and sand.

The dry densities of four Shelby tube samples of tailings were measured in the laboratory to range from 1.68 to 1.97 g/cm^3. The dry densities of materials within the GPA were estimated based on SPT blow counts from a relationship by Paikowsky et al. (1995) to range from 1.61 to 1.88 g/cm^3. SPT blow counts in tailings, corrected to $(N_1)_{60}$ values (Liao and Whitman, 1986), ranged from 2 to 21 (with an average blow count of 13 for 10 samples). Effective friction angles of tailings from two Shelby tube and two remoulded samples were measured in the laboratory to range from 34 – 35°. A third remoulded tailings sample yielded a bilinear shear strength relationship with an effective friction angle of 35° up to a normal stress of approximately 810 kPa; above a normal stress of 810 kPa, the effective friction angle and cohesion were approximately 19° and 280 kPa, respectively.

Silt-size tailings were generally described in the field to be moist, with gravimetric moisture contents ranging from 12.7 to 21.5% (average moisture content was 17.9% for 13 samples). Waste rock consisting of sand and gravel were typically described in core as dry, with gravimetric moisture contents ranging from 1.5 to 10.0% (average moisture content of 4.2% for seven samples). Stratigraphic changes in moisture content were vertically variable due to the heterogeneity of material, i.e., from moist tailings to dry waste rock. Wet material was encountered in the bottom 1.5 m of the SB-1 borehole during drilling in October 2012. In GP-1, frozen tailings were identified from core at 754.3 m a.m.s.l. (< 1 cm thick ice crystals), 752.8 − 752.5 m a.m.s.l. (< 1 cm thick ice lenses), 750.1 m a.m.s.l. (< 1 cm thick ice lens), and 743.4 − 742.8 m a.m.s.l. (non-visible ice, well-bonded).

4 Ground temperatures

The Pogo mine site is characterised by a continental climate with relatively low annual precipitation (~356 mm), relatively cool summers (mean of 10°C), and cold winters (mean of −13°C). Mean annual air temperatures measured on site ranged from −0.2°C to −3.0°C for the period of 2003 to 2009. DSTF ground temperatures were measured at the three instrumented sites to determine the influence of local climate on the facility, as ground temperatures may affect the physical stability, hydrology, and geochemistry of the stack.

Time-series temperature plots for each of the thermistor temperature sensors are shown in Figures 3A, 4A, and 5A (see Figure 2 for location of instrumented boreholes). Ground temperatures were observed to progressively decrease and thermally equilibrate to surrounding conditions over a two- to three-month period following installation. DSTF ground temperatures following the period of thermal equilibration are provided in Table 2.

At sensor RR-1 (elevation of 764.1 m a.m.s.l.), shallow ground temperatures ranged from 9.1°C to −6.2°C (Figure 3A, Table 2). The variability in temperature was likely caused by surface heating and cooling. The shallow ground thermal regime at this depth was observed to be below 0°C between the end of November 2012 and early July 2013. By mid to late April 2013, ground temperatures in the shallow RR-1 sensor began to continually warm in response to above-freezing air temperatures at the site. Ground temperatures in the shallow RR-1 sensor began to cool in early September 2013, presumably due to decreasing air temperatures at the site. As the thickness of DSTF materials over the shallow RR-1 sensor increases, seasonal ground temperature fluctuations at the sensor are expected to decrease and the lag time between surface and ground temperatures is expected to increase. Mid (746.2 m a.m.s.l.) and deep (736.1 m a.m.s.l.) thermistors at RR-1 indicate consistently negative ground temperatures measured at −0.8°C and −0.6°C, respectively.

DSTF ground temperatures measured at SB-1 shallow (elevation of 726.3 m a.m.s.l.) ranged from −0.1°C to −0.7°C, due to variability in surface temperature (Figure 4A, Table 2). Ground temperatures at SB-1 deep (702.0 m a.m.s.l.) were relatively stable, between −0.6°C and −0.7°C. The consistent decrease over the period of record is inferred to be caused by the slow dissipation of heat induced from drilling and backfilling with grout.

The shallow (738.5 m a.m.s.l.) and deep (716.0 m a.m.s.l.) thermistors at borehole GP-1 were consistently below 0°C and showed little variation in temperature (Figure 5A, Table 2). At the respective sites, ground temperatures were −0.7°C and −0.4°C. Similar to the deep sensor at SB-1, the minor cooling trend is inferred to be caused by the slow dissipation of heat originally induced by installation of the sensor.

At the borehole sites, DSTF ground temperature measurements indicate seasonally variable temperatures at shallow depth (< 7.6 m b.g.s., October 2012 DSTF surface) caused by heat transfer between the surface and the underlying tailings and waste rock. Temperatures measured between an elevation of 738 m a.m.s.l. and 716 m a.m.s.l. are relatively stable and below the depth of annual temperature variation in the ground (Figures 3A, 4A, and 5A). Temperatures at the mid and deep sensor sites were measured to range from −0.4°C to −0.8°C, indicating the presence of permafrost as thermally defined by temperatures at or below 0°C.

Pogo Mine’s baseline ground temperatures measured beneath naturally vegetated terrain indicate warm permafrost (> −2°C) (SRK, 2013). Across the mine site, permafrost is relatively thin and marginally below 0°C on southerly facing slopes vegetated with spruce and birch forests. In contrast, northerly facing slopes are characterised by colder permafrost, with the base of permafrost exceeding 90 m b.g.s. In 1999, baseline ground temperatures from naturally vegetated sites located up-gradient of the DSTF indicated permafrost temperatures ranging from −0.7°C to −1.8°C.

4.1 Tailings freezing characteristics

The phase state of water in the DSTF has significant bearing on the physical stability, surface water runoff characteristics, permeability, and geochemical reactivity of materials in the stack. To better understand the phase distribution of moisture in the DSTF, the freezing point depression of the tailings was assessed in terms of the soil textural properties and confining overburden pressure. The effects of dissolved ions in the tailings pore water and freeze partitioning of these ions during freezing were not considered as pore water chemistry estimation is not complete; however, these aspects of the soil-water system can greatly depress the freezing point.

The existence of unfrozen water in natural soil at below freezing temperatures has long been recognised (e.g., Taber, 1930; Beskow, 1935). Laboratory and field measurements demonstrate soil pore water freezes progressively, and not instantaneously, as temperature decreases below the initial freezing point. Additional factors influencing the freezing characteristics of soil include texture and mineral composition, initial water content, number of previous freeze-thaw cycles, confining pressure, and solute concentration of the pore water (Williams and Smith, 1989). These factors influence both the temperature at which pore ice initially forms (i.e., the ice nucleation temperature) and the fraction of liquid water that exists at below freezing temperatures.

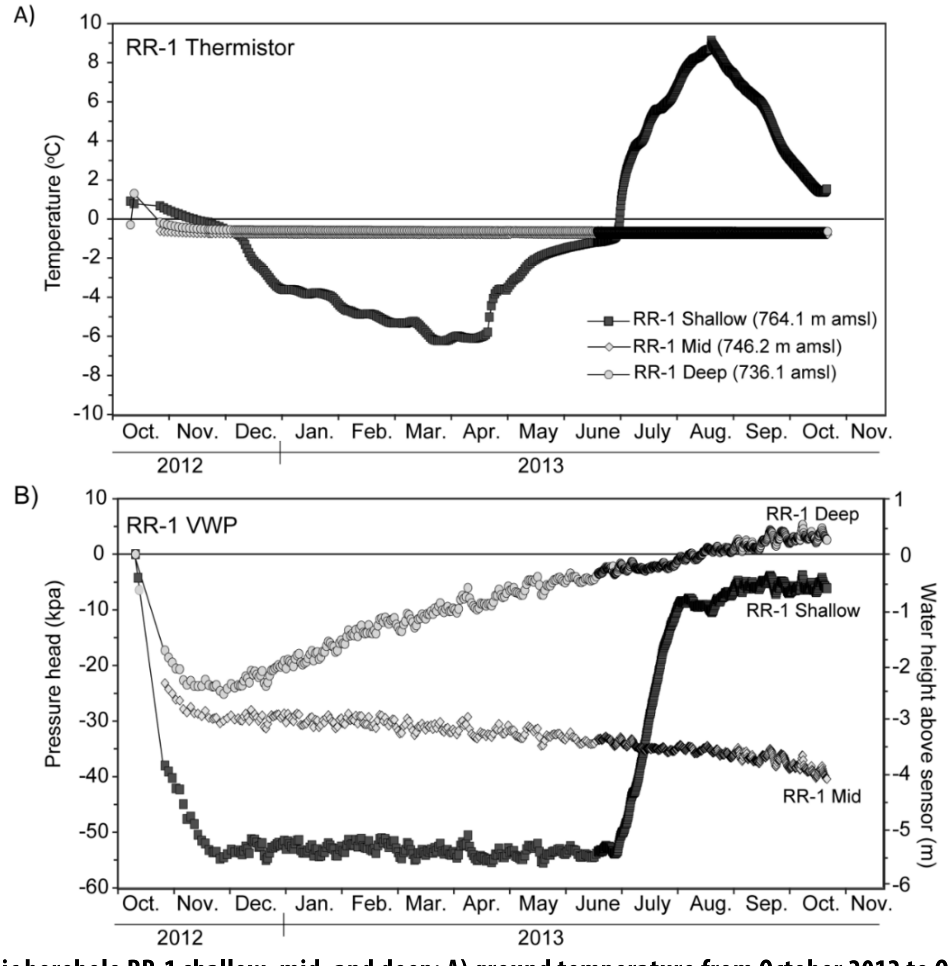

Figure 3 Sonic borehole RR-1 shallow, mid, and deep: A) ground temperature from October 2012 to October 2013, and B) VWP pore pressure from October 2012 to October 2013

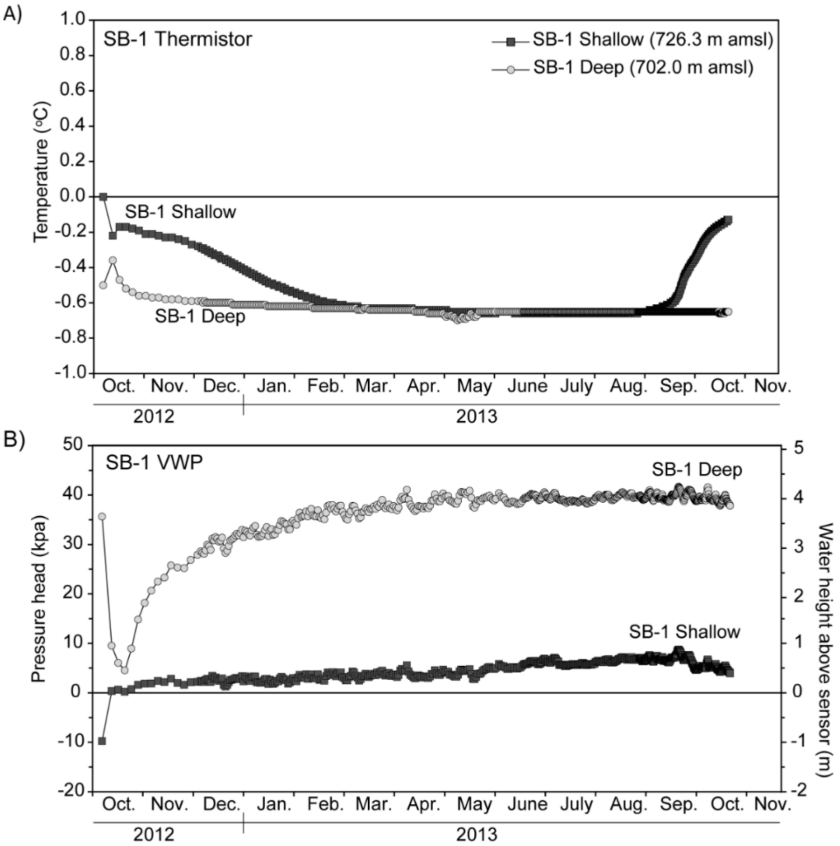

Figure 4 Sonic borehole SB-1 shallow and deep: A) ground temperature from October 2012 to October 2013, and B) VWP pore pressure from October 2012 to October 2013

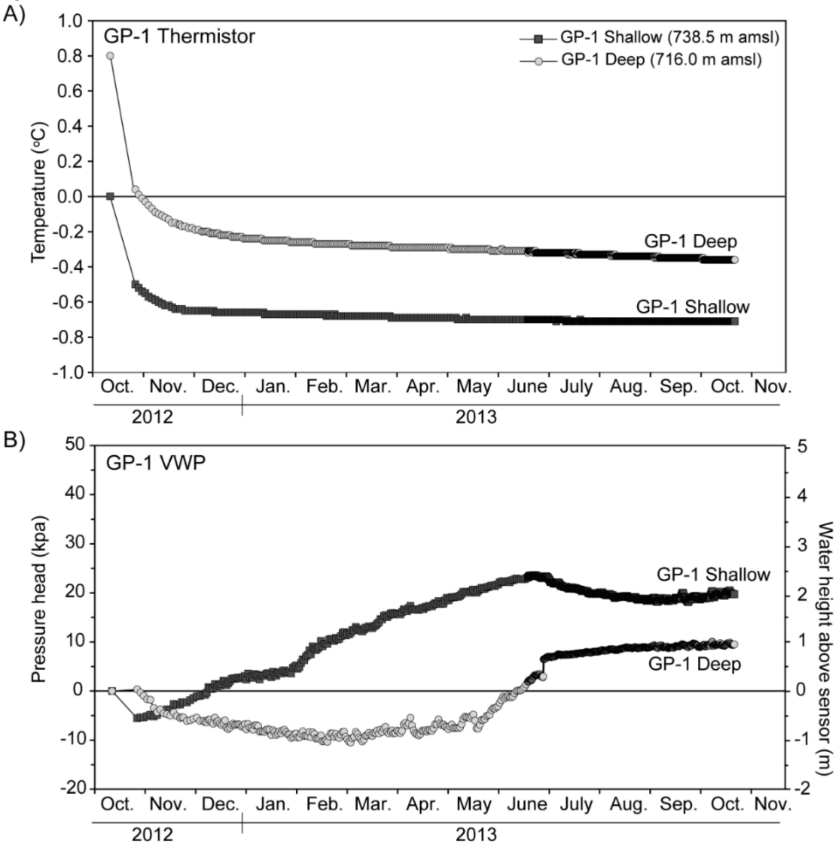

Figure 5 Sonic borehole GP-1 shallow and deep: A) ground temperature from October 2012 to October 2013, and B) VWP pore pressure from October 2012 to October 2013

Table 2 DSTF ground temperatures at borehole sites SB-1, GP-1, and RR-1

Site	Sensor description	Sensor depth [1] (m b.g.s.)	Elevation[2] (m a.m.s.l.)	Temperature (°C)	Measurement date/period
SB-1	Shallow	7.6	726.3	−0.1 to −0.7	10/3/2012 to 10/22/2013
SB-1	Deep	31.9	702.0	−0.7	10/22/2013
GP-1	Shallow	19.2	738.5	−0.7	10/22/2013
GP-1	Deep	41.8	716.0	−0.4	10/22/2013
RR-1	Shallow	0.6	764.1	9.1 to −6.2	10/1/2012 to 10/22/2013
RR-1	Mid	18.6	746.2	−0.8	10/22/2013
RR-1	Deep	28.7	736.1	−0.6	10/22/2013

1. Sensor depth is based on the depth below ground surface (b.g.s) at the time of sensor installation (October 2012).
2. Elevations are presented as metres above mean sea level (m a.m.s.l.).

4.1.1 *Estimated freezing point depression*

The freezing point depression of pore water attributed to overburden pressure and soil texture was estimated for DSTF tailings samples. The Clapeyron equation that describes two-phase equilibrium for water and ice in a soil pore space can be used to estimate the freezing point. Lixin et al. (1998) confirmed through laboratory measurements that the freezing temperature is inversely proportional to the applied overburden pressure for pure water and is consistent with the Clapeyron equation. A wet density of 1.95 g/cm^3 was used in the calculations, representing the average measured wet density of DSTF tailings. The freezing point depression attributed to overburden pressure, as defined by Lixin et al. (1998), was estimated to be insignificant (< 0.05°C) at the relatively shallow depths of the DSTF.

The freezing point depression related to textural characteristics of the DSTF tailings was also estimated using measured Atterberg limits, following Kozlowski (2007). These calculations were based on the measured plastic limits (16 to 23%) and gravimetric water contents (12.7 to 20.7%) for DSTF tailings. The freezing point of the tailings related only to soil texture is estimated to range from −0.2 to −0.7°C. The freezing point depression was estimated to increase at lower moisture contents due to the increase in surface tension of the pore water along the soil-grain boundaries.

4.1.2 *Estimated unfrozen water content curve*

The unfrozen water content curves for DSTF tailings, which indicate the amounts of liquid pore water present at subfreezing temperatures, were estimated for samples from boreholes RR-1, SB-1, and GP-1. The unfrozen water content curves were based on a semi-empirical model for phase change (Kozlowski, 2007). This model accounts for differences in the freezing point (ice nucleation temperature) and the progressive freezing of pore water below the initial freezing point. The model has shown good agreement with independently obtained laboratory measurements of soils ranging from sand to clay, and with unfrozen water content curves presented by Anderson and Tice (1973).

Freezing characteristics model inputs included grain size distributions, Atterberg limits, specific surface area (SSA) of the tailings, and moisture contents of the tailings. An average SSA value of 21 m^2/g was used in this study, which was based on the percentage of material passing the #200 sieve (< 75 µm) (Konrad, 1999). Reported SSA values for naturally occurring silts typically range from 18 – 83 m^2/g (Andersland and Ladanyi, 2004). The unfrozen water content can be expected to increase for sediments with a higher SSA value, such as soils consisting predominately of clay (Anderson and Tice, 1973).

The unfrozen water content curves for the DSTF tailings are shown in Figure 6. As expected, the amount of unfrozen water progressively decreases at temperatures below the materials' freezing point (ice nucleation temperature). The residual unfrozen water content at −12°C was estimated to range from 4 – 6%. The variability in the unfrozen water content over the expected range in SSA for naturally-occurring silt is less than 3%, assuming similar initial water contents. The unfrozen water content at −1°C is estimated to range between 7 and 11% of the dry mass; that is, between 36 and 65% of the moisture in the pore space may be liquid at −1°C.

5 Vibrating wire piezometers

Monitoring of VWPs has provided Pogo with pore pressure measurements to constrain the phreatic surface for the DSTF slope stability analysis. VWPs at the instrumented borehole sites recorded both positive and negative pore pressures (Figures 3B, 4B, and 5B). At RR-1 shallow (764.1 m a.m.s.l.), negative pore pressures were indicated, with a steady increase in pressure taking place at the end of June 2013 (Figure 3B). The increase in measured pore pressure corresponded with increasing ground temperature during the same period. The mid VWP sensor at RR-1 indicated consistently negative pore pressures that steadily decreased over time. This is in contrast to the deep VWP sensor at RR-1 (736.1 m a.m.s.l.), which indicated a steady increase from negative to slight positive pressure, equivalent to 0.5 m of water above the sensor.

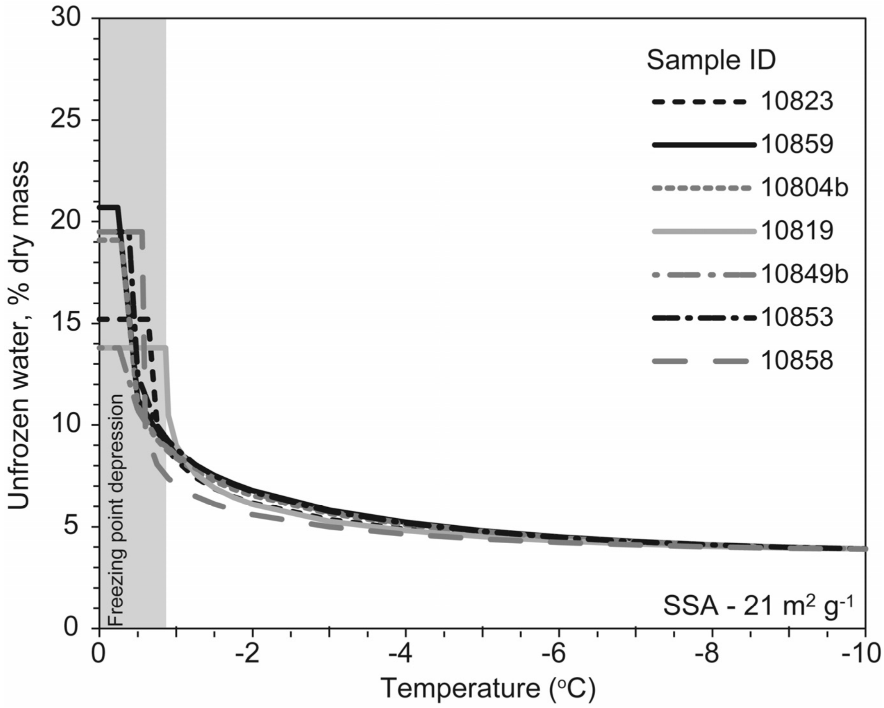

Figure 6 Estimated unfrozen water content curves for Pogo tailings, assuming fresh pore water

At VWP SB-1, positive pressures were measured at both the shallow and deep sensors (Figure 4B). At these depths, the maximum recorded pressures were 8.7 kPa and 41.7 kPa, equivalent to water heights above the sensors of 0.9 m and 4.3 m, respectively. The maximum recorded pressure at the SB-1 deep sensor equates to a phreatic surface elevation of 706.3 m a.m.s.l. The presence of a saturated zone near the bottom of SB-1 is further supported by the observation of wet core in the bottom 1.5 m of the borehole, i.e., from elevation 703 m a.m.s.l. to total depth, during drilling in October 2012.

At GP-1, positive pressures were indicated at the shallow and deep VWP sensors. The measured positive pressure of up to 23.6 kPa (equivalent to 2.4 m of water above the shallow sensor) was not expected, as observations during drilling did not indicate saturated ground in the vicinity of the sensor. At the GP-1 deep sensor, measured pore pressures were initially negative, but have steadily increased and have become slightly positive (equivalent to 1 m of water above the sensor) since mid-June 2013. A rapid increase in pore pressure was observed in late June 2013, which is equivalent to a 0.3 m increase in water height above the sensor.

The variable response and positive and negative pore pressures measured by the VWP sensors in the DSTF boreholes may be related to several factors. Positive pore pressures recorded at the site may be caused by a phreatic water surface above the sensor, as inferred to be present at the SB-1 deep sensor, or by isolated, perched, saturated zones within the DSTF. Negative pressures may be caused by either soil matrix suction in unsaturated materials or cryosuction where freezing conditions are present. Cryosuction occurs where temperature-dependent gradients in unfrozen water content cause negative pore pressures during soil freezing. At this time, damage to some of the sensors from possible freezing of water within some of the sensor diaphragms cannot be ruled out. Continued monitoring of the VWP sensors will provide a better understanding of pore pressures recorded at each sensor and the likely causes for the indicated pressures.

6 Acid-generating potential

Geochemical characteristics of DSTF materials are important in relation to water quality associated with the facility. To facilitate characterisation, the cores from sonic boreholes RR-1, SB-1, and GP1 were split for geochemical testing. Figure 7 presents the results of rinse pH and acid-base accounting (ABA) tests for the DSTF borehole samples. All samples (46 from tailings and 19 from waste rock) were submitted for rinse pH analysis. A subset of tailings and waste rock samples was submitted for ABA tests, which included paste pH, total sulphur, acid (HCl) extractable sulphur, and neutralisation potential (NP), using the modified Sobek method (MEND, 1991).

All rinse pH values were in the range of pH 7 – 9, and there were few clear trends related to borehole depth or material type (tailings versus waste rock) (Figure 7A). Nearly all samples were classified as non-potentially acid-generating (non-PAG) based on neutralisation potential (NP) to acidification potential (AP) ratios greater than three (NP/AP > 3) (Figure 7B). This conservative criterion was set to allow for uncertainty in the mineralogical occurrence of NP.

Values of AP ranged from 3.8 – 18.1 kg of calcium carbonate per tonne (kg$CaCO_3$/t) in waste rock and 2.8 – 11.6 kg$CaCO_3$/t in tailings (Figure 7B). Total sulphur concentrations in waste rock and tailings ranged from 0.14 – 0.6% S and 0.11 – 0.38% S, respectively. The maximum hydrochloric acid (HCl) digestible sulphur concentration in any sample was 0.05% S, indicating that the majority of sulphur was likely present as sulphide. Neutralisation potential (NP) values ranged from 18.5 – 49.0 kg$CaCO_3$/t in tailings and 17.0 – 54.5 kg$CaCO_3$/t in waste rock (Figure 7B).

7 Dry stack tailings facility characteristics and implications for closure

This study contributes to further understanding of the geotechnical, thermal, hydrologic, and geochemical conditions of the Pogo Mine DSTF to support closure planning. Specifically, this study confirms specific aspects of the DSTF operational construction and closure plans while narrowing the focus of data collection for future closure planning, as discussed below. In addition, this study provides an example of conditions within a dry stack tailings facility in a continental, subarctic climate that is pertinent for planning, design, permitting, operation, and closure of dry stacks in similar climates.

The geotechnical field and laboratory testing program indicated that effective friction angles and dry densities of in situ DSTF materials are consistent with limited laboratory testing of pilot and DSTF materials from previous slope stability analyses (AMEC, 2004; SRK, 2011). The results of the geotechnical investigation, thermal monitoring, and analyses indicate the presence of both frozen and liquid water within the DSTF; these results indicate that modelling the physical stability of the DSTF in an unfrozen state is most appropriate for long-term assessment. The pore pressures measured by VWPs installed within the boreholes provide evidence for the presence of a phreatic surface and isolated, perched saturated zones within the dry stack. As discussed in Section 5, positive pore pressures near the bottom of SB-1 suggest a phreatic surface at an elevation of 706.3 m. The material properties and phreatic surface from this study have been incorporated into the limit equilibrium DSTF slope stability model, which indicates static and pseudostatic stability of the

DSTF. The liquefaction potential of materials within the DSTF was also evaluated using the methods of Youd and Idris (2001): SPT blow counts within the saturated interval indicated in SB-1, along with seismic parameters from the design M8.0 earthquake (AMEC, 2004), show stability of the DSTF against liquefaction. The stability results of this study support operational material placement practices and the planned closure configuration of the DSTF, i.e., utilising operational slope angles for closure.

In addition, the geotechnical evaluation has provided new insight into the thermal and hydrologic conditions of the facility. DSTF ground temperatures confirm the presence of permafrost, as thermally defined by temperatures at or below 0°C. Local conditions beneath naturally-vegetated terrain also permit for the persistence of contemporary permafrost. The presence of permafrost within the DSTF is inferred to result from local air and ground temperatures and from the relatively low amounts of solar radiation received in the valley where the facility is located. Continual placement and burial of tailings and waste rock may also contribute to entrapment of cold zones within the stack. Over time, the DSTF can be expected to thermally evolve as additional material is added and in relation to changes in local climate and microclimatic effects at the surface, i.e., presence of surface water, snow accumulation, and post-closure revegetation.

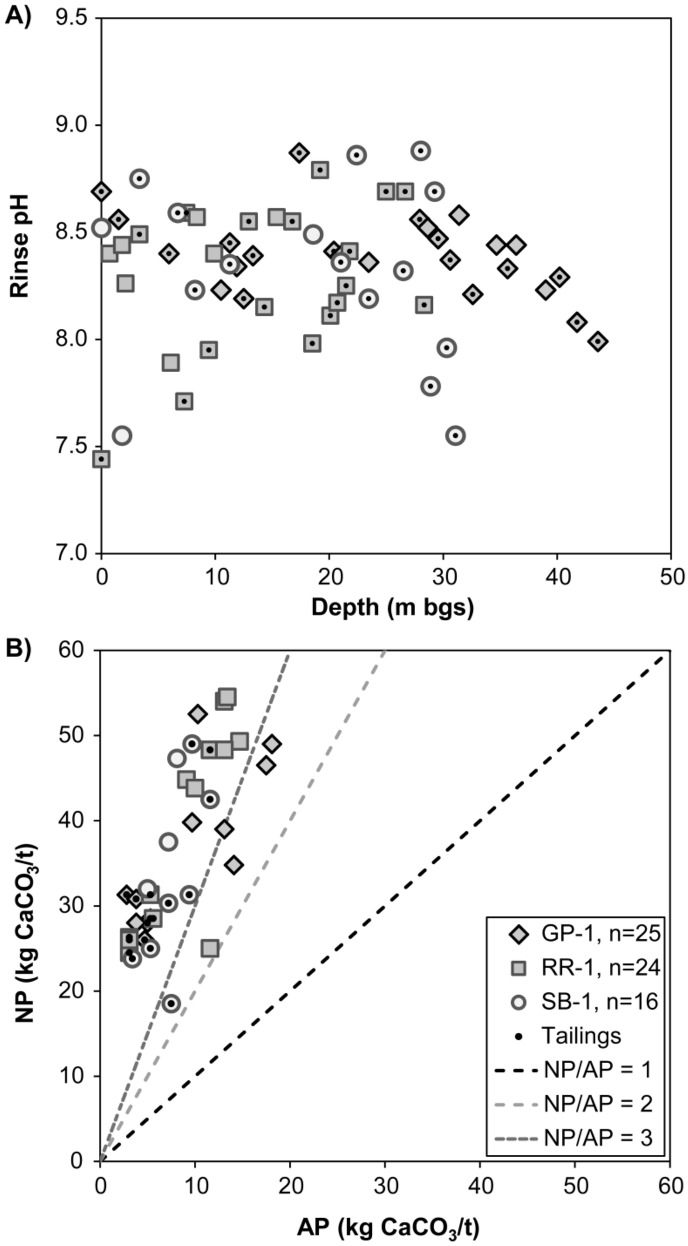

Figure 7 A) Rinse pH versus depth and B) neutralisation potential (NP) versus acidification potential (AP) for tailings and waste rock samples recovered from boreholes RR-1, SB-1, and GP-1

The presence of unfrozen tailings within the DSTF can be inferred from the relatively warm ground temperatures, the fine-grained nature of the tailings, observational evidence from the drill core, and the estimated freezing characteristics. Partially-frozen material with appreciable unfrozen water is also likely, given the fine-grained nature of the tailings and measured ground temperatures (Figure 6). Isolated zones of frozen ice-bonded tailings with minimal ice segregation have been identified at shallow depths (< 15 m b.g.s.), as evident from core recovered at GP-1. The coarse-grained waste rock interlayered between tailings may also be frozen at some locations where moisture is present. Whether frozen zones are a result of temperatures at the time of placement, changes in soil texture, or other factors is uncertain at this time. Due to the indicated presence of unfrozen water in the DSTF and uncertainty related to future climate, evaluation of the physical and chemical stability of the DSTF for closure has assumed an unfrozen state. Nevertheless, monitoring of ground temperatures during mine operation may provide constraints on the thermal behaviour of the DSTF for future closure evaluation.

Monitoring of pore pressures during mine operation will provide valuable information on seasonal and long-term trends of water within the DSTF. The presence of permafrost in the DSTF indicates the permeability of in situ DSTF materials will likely be lower than the permeability of unfrozen DSTF materials, resulting in higher runoff and lower seepage than would be predicted in an unfrozen state. Evaluation of surface water and groundwater monitoring data from and adjacent to the DSTF may further constrain components of the DSTF water balance, including runoff, seepage, and flow-through drain flux.

Geochemical analyses of tailings, mineralised waste rock, and nonmineralised waste rock samples indicate neutral to basic pH and the predominance of non-PAG material. The data indicate that acidic drainage associated with the DSTF is unlikely. Evaluation of the long-term metals-leaching potential of DSTF materials through laboratory testing, comparison to operational monitoring data, and water quality modelling may inform selection and design of a closure cover system.

8 Conclusions

A multidisciplinary investigation of the Pogo Mine DSTF was performed to support closure planning. Key geotechnical, thermal, hydrologic, and geochemical findings have been presented and are summarised below:

1. Thermal monitoring and analysis show permafrost within the DSTF, but closure evaluation has assumed an unfrozen state to account for unfrozen pore water and climate variability.
2. Pore pressure measurements and drilling observations indicate a phreatic surface near the base of the DSTF.
3. Even with the indicated phreatic surface, the density and shear strength of DSTF materials indicate static and pseudostatic slope stability of the stack and stability against liquefaction.
4. Geochemical analyses of DSTF materials show that acidic drainage from the stack is unlikely.

These findings serve to support operational material placement practices and elements of the closure plan for the DSTF, narrow the focus of data collection for future closure planning, and provide an example of conditions for design, operation, and closure of dry stack tailings facilities in similar climates.

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